"'Movement of sediment in the
nearshore zone, Gibraltar
Point, Lincolnshire' by
Robert Edward Dugdale, B.Sc.
Thesis submitted to the University
of Nottingham for the degree
of Doctor of Philosophy,
May, 1977."

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ABSTRACT

A descriptive sediment movement model has been created for an area of the nearshore zone near Gibraltar Point, Lincolnshire on the basis of evidence from studies of sediments, sandbank and channel morphology, bedforms, tidal currents and sediment tracer experiments. The area is subject to linear tidal currents which have created a system of tidal current ridges,tidal channels and an ebb-tidal delta. Sediment movement associated with these sandbanks and channels was found to have a net northerly drift related to an ebb tidal residual in the Boston Deep, the largest channel in the area. Sediment circulation around the sandbank system was considered to be essentially closed with a large sediment storage element represented by the sandbanks. An area of the foreshore was identified as a possible location for movement of sediment from the nearshore zone to the foreshore zone.

Six Woodhead seabed drifter experiments were conducted to assess the validity of the sediment movement model. The net northerly drift of the sediment within the sandbank system was confirmed and was found to extend as far north as Ingoldmells Point. Movement of sediment from the nearshore zone to the foreshore zone was confirmed at the location suggested in the sediment movement model and was also predicted at Ingoldmells Point. The time of stranding of seabed drifters was found to coincide with periods of winds blowing offshore and from the north-east and with

periods of increasing tidal current velocity as the lunar tidal cycle approaches spring tide conditions. Movement of sediment from the nearshore zone to the foreshore zone may also occur under these environmental conditions.

A study of the historical development of the sandbanks suggested an overall decrease in the size of tidal current ridges since 1871 which may be related to a decrease in the amount of sediment available for the maintenance of the sandbanks. A ness south of the Skegness Middle sandbank was interpreted as a morphological expression of foreshore adjustment to the migration of sediment from the nearshore zone to the foreshore zone at this location.

ACKNOWLEDGEMENTS

The work presented in this thesis was begun whilst the author held the post of Demonstrator in the Department of Geography, University of Nottingham. He wishes to thank Professor R.H. Osbourne, Professor C.A.M. King and the Staff of the Department for providing not only a wide range of facilities but also a stimulating working environment. Professor C.A.M. King has supervised this work with more patience than is normally expected and has contributed a great deal to its execution. Dr. M.J. McCullagh and Dr. P.M. Mather provided valuable advise on programming problems and automated cartography. Mrs. E. Piper gave welcome assistance with the laboratory work and Mr. M. Cutler drew many of the diagrams in this thesis.

A special acknowledgement is made to Mr. K.R. Winter who suffered the fieldwork at Skegness with rare good humour and provided excellent companionship even in times of adversity. Without his assistance this thesis may never have been completed. Finally, my wife Jennifer not only typed this thesis but also provided support and encouragement and was at all times patient and understanding, often despite considerable lack of appreciation.

CHAPTER ONE

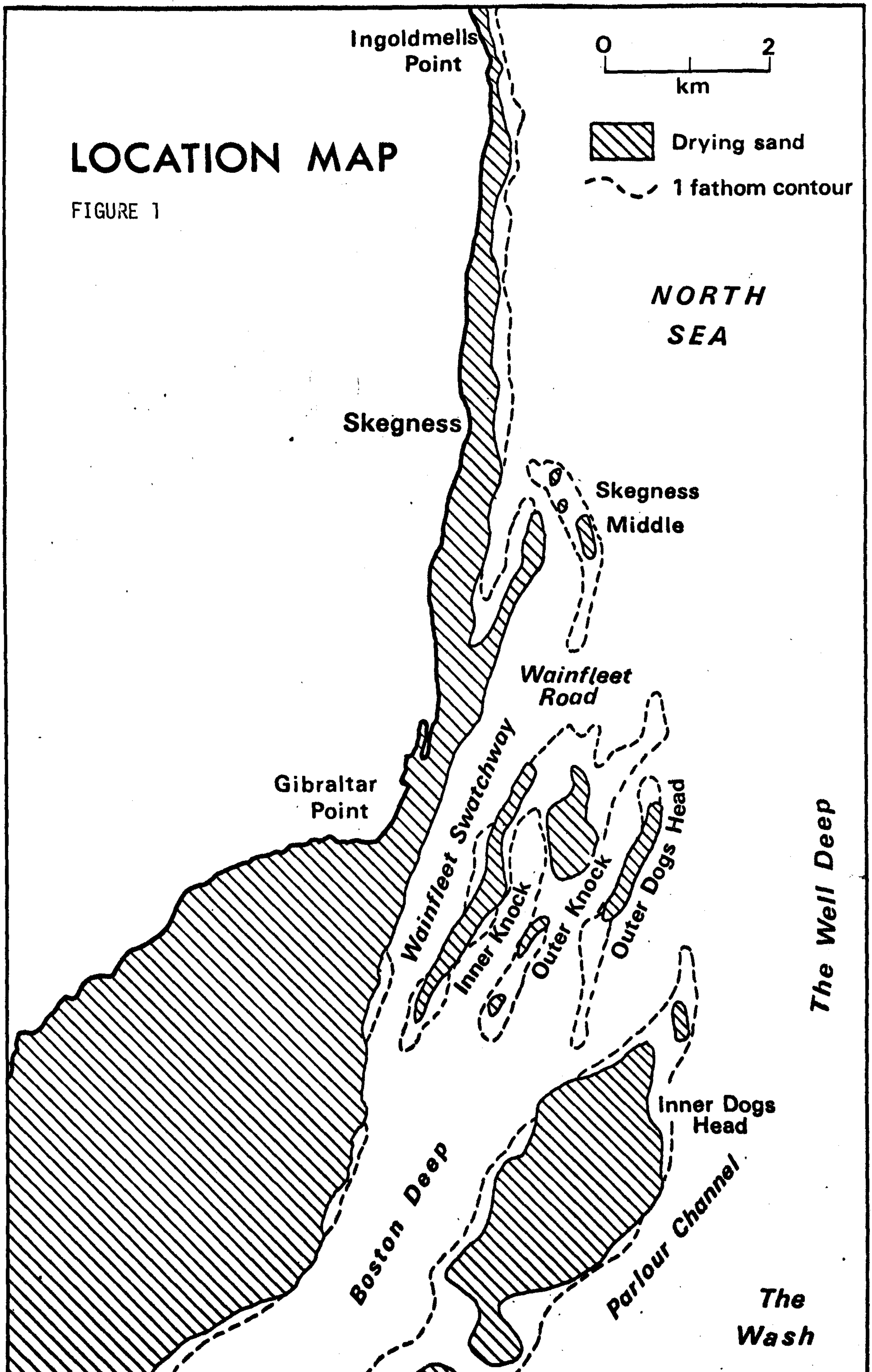
INTRODUCTION

The work presented in this thesis is intended to create a sediment movement model for a nearshore zone dominated by tidal sandbanks, and to assess the possible implications of this sediment movement as regards beach morphology and areas of erosion and deposition on a contiguous shoreline.

The area of study is located south-east of Skegness, Lincolnshire in the mouth of the Wash estuary. (Figure 1). The beach between Ingoldmells Point in the north and Gibraltar Point in the south is terminated in a seaward direction by a relatively steep slope of 3 degrees which begins at the level of low water at spring tides and descends to a shelf at approximately 9m. below low water at spring tides. This shelf, cut in glacial boulder clays, is approximately 7km. wide and is terminated seaward by another steep slope which descends to 23m. in the Well Deep, the central channel of the Wash. Superimposed on the shelf are a series of linear and sigmoidal sandbanks created by strong linear tidal currents in the area (Robinson, 1964).

The geomorphology of the nearshore zone can be considered in the framework of a process-response system (Chorley and Kennedy, 1971) which can be subdivided into a cascading system and a related morphological system.

The cascading system represents the dissipation of energy in terms of the processes operating in the area, dominantly tidal currents, which are manifested in the movement of mass in terms of water and beyond the threshold of sediment entrainment the transport, sorting and deposition of sediment. The product of the cascading system, partly self regulating due to negative feedback, is the morphological system represented firstly by


LOCATION MAP
FIGURE 1
Ingoldmells Point
0 2
km
Drying sand
1 fathom contour
NORTH SEA
Skegness
Skegness Middle
Wainfleet Road
Wainfleet Swatchway
Gibraltar Point
Inner Knock
Outer Knock
Outer Dogs Head
The Well Deep
Inner Dogs Head
Boston Deep
Parlour Channel
The Wash

the sedimentological bedforms and secondly by the gross areal and morphological attributes of the sandbanks and channels.

Ideally the primary objective of this thesis, a sediment movement model, should be created by monitoring actual sediment movements. This objective can be achieved by use of fluorescent or other suitably marked tracers. Unfortunately such methods are both temporally and spatially restricted due to the high energy levels operating in the system which dissipate the relatively small amounts of marked sand grains compared to the almost infinite population of sand grains on the sandbanks and in the channels. At best marked sand grains can be recovered after two complete tidal cycles. Consequently the movement of sediment must be inferred from the attributes of other cascading and morphological subsystems, assuming the relationship between sand grain movement and these attributes is known or can be established empirically.

Since the common denominator of this thesis is the sediment in the nearshore zone the spatial distribution of sediment size was sampled and mapped in detail. Trends in the spatial change of sediment size and sorting could provide evidence of sediment transport paths.

Two morphological subsystems were studied in detail. The morphology of the sandbanks and channels was monitored using aerial photographs and echo-sounder equipment. Both the plan shape and cross-sectional attributes of the sandbanks and channels provide useful evidence of the spatial pattern of sediment movement. The subsystem of bedforms found on the banks and in the channels was classified on the basis of spacing and morphological characteristics. A map of bedform distribution was constructed based on this classification and field survey. The type, orientation and migration rates of bedforms provided evidence of sediment transport paths and the energy level of processes operating on the sandbanks.

The cascading subsystem of tidal currents was monitored at five locations using a boat-mounted current meter. Measurements were made over one complete tidal cycle to monitor residuals of tidal current flow. Velocity profiles were measured to predict the time of initiation of sediment movement in relation to tidal flow and to produce a bedload transport index.

The direction and amount of sediment movement inferred from the above subsystems were confirmed at several locations using tracer sand marked with fluorescent dye. A sediment movement model was constructed from the available evidence.

Much of the evidence from which the sediment movement model is constructed is based on observations at a point in space and time. Woodhead seabed drifters on the other hand, move over the seabed with a velocity at, or near, that of bottom tidal currents. Since only the release and recovery points are known, little may be deduced about the paths followed by the drifters. However, drifters will respond to residuals of tidal current flow. Release and recovery patterns of drifters were employed to confirm large scale trends in sediment movement suggested by the sediment movement model.

Woodhead seabed drifters also provided vital evidence regarding the interaction between the nearshore and foreshore sediment systems in the area. The locations of strandings of drifters were found to be significant in relation to the morphology of the nearshore and foreshore zones. Finally bathymetric surveys of the area since 1871 were studied to confirm the constancy of the above relationship through time and to assess the incidence of erosion and deposition on the foreshore in relation to sediment movement in the nearshore zone.

The area has a mean tidal range of 2.98m. on neap tides and 6.96m. on spring tides. The sandbanks are exposed for approximately 3 hours around low water on spring tides with a range exceeding 5.6m. Since the boats used for fieldwork were moored on a tidal river, the Steeping, and could only leave and re-enter the river at highwater, fieldwork was confined to periods when daylight coincided with a full tidal cycle from highwater to highwater at spring tides. This constraint limited fieldwork to the months of May, June, July, and August in the summers of 1971 to 1975 inclusive. During each of these four month periods suitable spring tides were found on approximately 24 days. In practise inclement weather conditions allowed approximately 14 days of fieldwork each year.

During this enforced prolonged fieldwork period of five years the position and morphology of the sandbanks being investigated could have changed, negating the usefulness of data, collected before and after the change, in constructing a sediment movement model.

Reconnaissance aeroplane flights were made in April 1971 and March 1975 over the exposed sandbanks during spring tide conditions. Photographs taken on each trip demonstrated no recognisable change in either the morphology or position of the sandbanks in the interim period. Based on this evidence it is reasonable to assume that the sandbanks have been in dynamic equilibrium with the operative processes during the fieldwork period. Data collected at any time in the five year period can, therefore, be assumed to be information relating to parts of one system which, in a short temporal sense, is in equilibrium.

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East Mid. Geog., 3, 307-321.

CHAPTER TWO

GEOMORPHOLOGICAL BACKGROUND

Sedimentary deposits, coastal morphology and historical evidence indicate variable erosion and accretion along the Lincolnshire Coast in post-glacial times.

East of the Lincolnshire Wolds is a buried wave cut platform, eroded into the Chalk, which is everywhere below sea level. Against the inland margin of the wave cut platform, a former cliff line, and resting on the wave cut platform is a deposit of glacial boulder clays approximately 25 m. thick which now rises between 5 and 30 m. above the present sea level and forms the Middle Marsh. The resistance to erosion of this boulder clay may be responsible for the location of some of the present coastal headlands including Chapel Point and Ingoldmells Point (Barnes and King, 1953).

The post-glacial development of the Lincolnshire coast has been outlined by Swinnerton(1931, 1936). In the period immediately after glaciation the sea level would be much lower than at present and the land would extend seaward of the present coastline for a considerable distance. Forests were established on the exposed surface of the boulder clay. During the post-glacial rise in sea level the coast became progressively inundated by seawater and deteriorating drainage conditions initiated the formation of a peat layer enclosing the stumps of the former forest. As inundation continued tidal saltmarsh silts and clays were deposited over the peat layer and eventually covered a substantial part of the Lincolnshire coast. The settling of tidal clays and silts requires almost still water conditions. Much of the present coastal areas were probably shielded from waves approaching from the North Sea by an offshore barrier, probably a broken range of morainic hills extending from the Norfolk Coast to Spurn Point, represented today by the Protector Overfalls and the Inner Dowsing 15 km. seaward of the present coastline. The area of deposition of tidal saltmarsh silts and clays is known as the Outmarsh.

A reduction in the rate of rise of sea level during the Bronze Age period resulted in the formation of freshwater marsh clays and a subsequent development of a peat layer in the Iron Age period. In Roman times tidal silts were again deposited suggesting an increase in the rate of rise of sea level. Historical evidence collated by Owen (1952) suggests that the offshore barrier was finally breached in the thirteeth century due partly to increased wave action during a particularly stormy period and partly to a rise in sea level. About this time a beach and associated dune line would be formed by wave and wind action much closer to the present shoreline than the offshore barrier.

The subsequent history of the Lincolnshire coast represents an adjustment of the coastline to the geomorphological processes operating and attempts by man to resist coastal erosion. The historical evidence presented by Owen (1952) for the last 700 years suggests a series of minor breaches of the coastal defences ensuring the gradual retreat of the coastline landwards, the construction of new protecting banks and the abandonment of land seaward of the new coastal defences. Between Mablethorpe and Skegness five medieval parishes have been lost to the sea and the villages of Thrusthorpe, Sutton, Chapel St. Leonards and Skegness have had to change their sites. Along this section of the coast the coastline has moved landward by approximately 0.8 km. during the last

400 years. This coastline retreat is confirmed by the removal of the medieval sea defence, the Roman Bank, in the areas between Sandilands and Mablethorpe. Erosion remains the dominant feature of the coastline between Mablethorpe and Ingoldmells Point to the present day.

The coastline between Skegness and Gibraltar Point suffered erosion as late as the fifteenth century with the loss to the sea of the North Common and the original ness of Skegness. Inundations occurred as late as the mid-seventeenth century but for the last 150 years accretion has been the dominant process. The area between Skegness and Gibraltar Point is formed of two dune lines, the western and the eastern, which enclose an area of mature marsh, the present beach being east of the eastern dune line. The earliest reliable map of the area, made by Armstrong in 1779, shows the coastline west of the present coast and coincident with the western dune line. Sandy ridges in the mature marsh contain shell fragments and pebbles, are morphologically similar to ridges on the present beach and probably represent the beach area in the late eighteenth century. Davies (1962) presents borehole data from a site west of the River Steeping at Gibraltar Point. No post-glacial silts and clays were found in the borehole, only a 4.5 m. thick lens of sand, resting on boulder clay, extending inland for an unknown distance. The absence of post-glacial silts and clays is probably due to erosion by the River Steeping and the sand probably represents a beach or spit deposit extending the southern end of the western dune line. Between 1824, the date of the eariest Ordnance Survey map of the area, and 1897 the eastern dune line and the present beach were established.

Robinson (1964) suggested reasons for the contrasting areas of erosion and accretion along the Lincolnshire coast. In a study based on the diffusion of Woodhead sea bed drifters from a location off Spurn Point, recovery points of drifters suggested a net southerly movement of tidal currents and sediment along the Lincolnshire coast. Tidal currents were considered to be a more important sediment transporting agent than long shore drift associated with wave action as suggested by Kidson (1961). This inshore southerly movement of sediment is in sharp contrast to the offshore northerly movement of sediment from a bedload parting off the Norfolk coast to a bedload convergence off Flamborough Head as recognised by Stride (1963, 1971) on the basis of sandwave orientation. Recovery points of drifters were found to concentrate around Saltfleet Haven north of Mablethorpe and Gibraltar Point. At both these locations offshore bank systems with associated ebb and flood channels were found which indicate convergence of tidal flows, carrying large amounts of sediment, towards the coastline. No drifters were found in the area between Mablethorpe and Huttoft, a zone of erosion, suggesting tidal transport of sediment parallel to the coastline. Some drifters did not reach the foreshore at Gibraltar Point until 91 days, or even 121 days, after release. This slow time of arrival is probably related to the complex path which drifters would have to follow around the banks in the area before being carried to the beach by tidal currents under favourable conditions.

King (1964) confirmed the role of the banks in the convergence of tidal currents in the Gibraltar Point area and also suggested that the banks provide significant protection to the foreshore from approaching waves allowing accretion to occur. This observation is supported by the relatively fine sediments on the lower foreshore compared with the upper foreshore suggesting lower energy wave conditions.

Both Robinson (1964) and King (1964) noted the southerly movement of the ness, the zone of maximum accretion, in the Gibraltar Point area and related this to the southerly movement of the Skegness Middle bank since 1828 which impinges on the foreshore immediately north of the ness.

A substantial supply of sediment to the foreshore in the Gibraltar Point area is confirmed by the beach morphology and the existance of a spit extending the eastern dune line southwards. In morphological terms the beach is of a ridge and runnel type. Such beaches occur where there is a surfeit of sediment, the ridges representing the attempt by waves to construct an equilibrium gradient on a too flat overall gradient (King and Williams, 1949). King (1973) discussed the rate of accretion on the foreshore based on repeated profiles of the beach between 1951 and 1971. The rate of landward movement of the beach ridges was analysed by trend analysis and the trend of ridge height, which is closely related to the amount of accretion was analysed by time series methods. Both analyses showed general trends of accretion in the area with minor cyclic fluctuations on some profiles. Profile 4, located on the apex of the ness recorded the fastest rate of accretion with a mean rate of accretion of $89m^2$ /year for the period 1953 to 1971, providing a total accretion of $1,590m^2$ reflected in a 366m. seaward advance of the foreshore since 1951.

The growth of the spit at Gibraltar Point was also analysed by trend analysis suggesting an increase in size over the last 18 years with a slight reversal in recent years. The spit is constructed by waves drifting material southwards along the beach at high water when the shielding effect of the banks is at a minimum. Robinson (1964) suggested that the relatively small size of the spit compared with Spurn Point can be accounted for partly by the decrease in the amount of the southerly movement of sediment along the Lincolnshire coast and partly by the parallel nature of the banks relative to the coastline, encouraging an eastward extension of the foreshore rather than a southerly extension of the beach.

The source of sediment in the Gibraltar Point area can be inferred from evidence of previous geomorphological process operating on the grains preserved on the grain surface, mineralogy and sediment transport paths. Sand sized grains of sediment both from the beach and banks have been studied by electron microscopy (King, 1973). The surface of the grains had a weathered appearance in the form of linear peeling and showed evidence of previous glacial action in the form of parallel lines on the grain surface. Some marine features were also evident. Davies (1962) found that heavy minerals formed 10 - 15% by weight of the beach sand and that quartz accounted for 80 - 90% of the light minerals. Analysis of heavy minerals showed that the suite of minerals was similar to group 'E' of Baak (1936) which is common over all parts of the floor of the western North Sea and similar to that of the glacial deposits of Holderness. Since sediment movement along the Lincolnshire coast is in a southerly direction the eroding cliffs of Holderness and the floor of the North Sea north of the Wash would appear to be the probable source of sediments found in the Gibraltar Point area.

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CHAPTER THREE

THE SEDIMENTS

The mean grain size, sorting and skewness of the unconsolidated clastic sediments which form the sandbanks, considered both at a point and spatially, can be used as qualitative indirect indicators of the direction and amount of sediment movement. The mean grain size of the sediment will be in equilibrium with the power of the tidal currents responsible for their entrainment, transport and deposition (Bagnold, 1966; this thesis Chapter 6). Sediment is subject to sorting proportional firstly to the distance it is moved by a particular water flow and secondly to the power of the water flow (Folk and Ward, 1957). Skewness has been used to differentiate depositional environments (Mason and Folk, 1958) and to differentiate quieter from more vigorous environments of deposition of sediment. A negative skewness is indicative of an absence of fines, a characteristic of more energetic environments(King, 1973).

A sampling plan was devised which was subject to both practical and theoretical considerations.

THE SAMPLING PLAN

A sampling plan must ensure that the properties of the sample reasonably approximate the properties of the population. Discussions of sampling plans which satisfy the above criterion are contained in Krumbein and Graybill (1965) and Chorley (1967). Four problems must be faced : (a) for the purposes of comparison the samples should represent a population which was contemporaneously subject to the geomorphological forces operating in the system, (b) how many samples are required ?, (c) how big must each sample be ?, and (d) at which locations should samples be taken ?.

To satisfy criterion (a) all the sediment samples discussed in this chapter were collected on the three consecutive days of the highest spring tides of 1973. Tidal currents associated with these tides could be expected to be the strongest of the year, excepting possible storm conditions, producing surges, associated with spring tides at other times. Sampling during periods when tidal currents are at a maximum ensures that no lag effect from less strong tidal currents will be present in the sediment samples. That is, all samples taken on the above days will be in equilibrium with tidal currents at that time and not with tidal currents associated with some lower energy spring or neap tides.

The number of samples required is theoretically controlled by the variability exhibited by the population. In practical terms, particularly as regards intermittently exposed sandbanks, as many samples as possible must be taken in the time available, paying particular attention to criterion (a) discussed above.

The size of the sample required depends upon the operations which are to be carried out on the sample after collection. In this case the weight of grains falling into certain size categories (phi scale), related to the geometrical and hydrodynamic properties of the grains, is of prime concern. The sample must be large enough to contain a representative weight of the biggest particles present. Since the largest grains found on the sandbanks are of the order of 8 mm. in diameter a sample of approximately 150 gms. dried weight was considered sufficient.

Chorley (1967) lists six types of sampling plans covering random, simple random, serial stratified, systematic grid and nested sampling. Stratified and serial sampling plans are not appropriate to the present problem. Random and simple random plans are commonly used in sedimentological research. However, such plans necessitate the rapid recognition of randomly selected sites. Since no comprehensive system of locational reference points is available on the sandbanks such plans were rejected on the basis of time needed to collect samples. If significant local variations of the sampled population are thought to occur it is usual to adopt the nested sampling plan. This type of plan is appropriate for the statistical assessment of within and between group variability provided major units can be selected by some random process. Since statistical treatment of the sediment samples was not contemplated and considering the time consuming nature of this method the simpler systematic grid sampling plan was adopted.

Considering the time available for sample collection a 100 m. square grid was adopted for sampling the Inner Knock, Outer Knock and Outer Dogs Head. The Inner Dogs Head, a sandbank with a much greater areal extent than other sandbanks in the study area, was sampled on a 200 m. square grid. The origin of the grid was marked by a stake and compass bearings taken to a minimum of three recognisable landmarks on the coastline. Having established the location of the origin, the grid was laid out using a compass and tape measure. The primary axis of the grid was established centrally along the longest axis of the sandbank and marked at either 100 m. or 200 m. intervals depending on the location of the grid. Subsequently traverses were made across the sandbanks and samples collected at grid intersections. Samples were collected using a 15 cm. square stainless steel shovel to a depth of 2.5 cm. below the sand surface. The samples were placed in plastic bags and serially numbered using waterproof ink on plastic coated cards. The locations of the grids over four major sandbanks studied are shown in Figure 2 . Sampling of the sediments in the channels was conducted using a cable mounted U.S.B.M. 54 bucket sampler (Figure 3) (F.I.A.S.P., 1963). The body of the sampler is constructed of cast steel and weighs 20 kgms. The rotating bucket, or scoop, is spring loaded and is triggered by a slackening of the tension in the suspension cable when the sampler rests on the seabed. The capacity of the scoop is 175 c.c. Sediment samples were taken at approximately 200 m. intervals along the central axes of the channels. The boat was manouvered an estimated 200 m. between sample locations, anchored, and compass fixes made to landmarks on the coastline. The resulting sampling pattern is shown in Figure 4.

As sampling proceeded difficulties were encountered related to the nature of the bottom sediments in the channels. A common occurrence at many sampling stations was the failure of the sampler to close because of gravel sized particles trapped in the mouth of the scoop. Any sand collected by the scoop would be washed out during the passage of the sampler from the bottom of the channel to the sea surface. A common association with trapped gravel was a glutinous grey clay smeared on the underside of the sampler. This association of gravel and clays has been interpreted by the I.G.S. (1972) as glacial till with a thin lag deposit of gravels. Locations where sand samples were successfully collected were found to be in areas where sandwaves were common on channel floors. (Chapter 5).

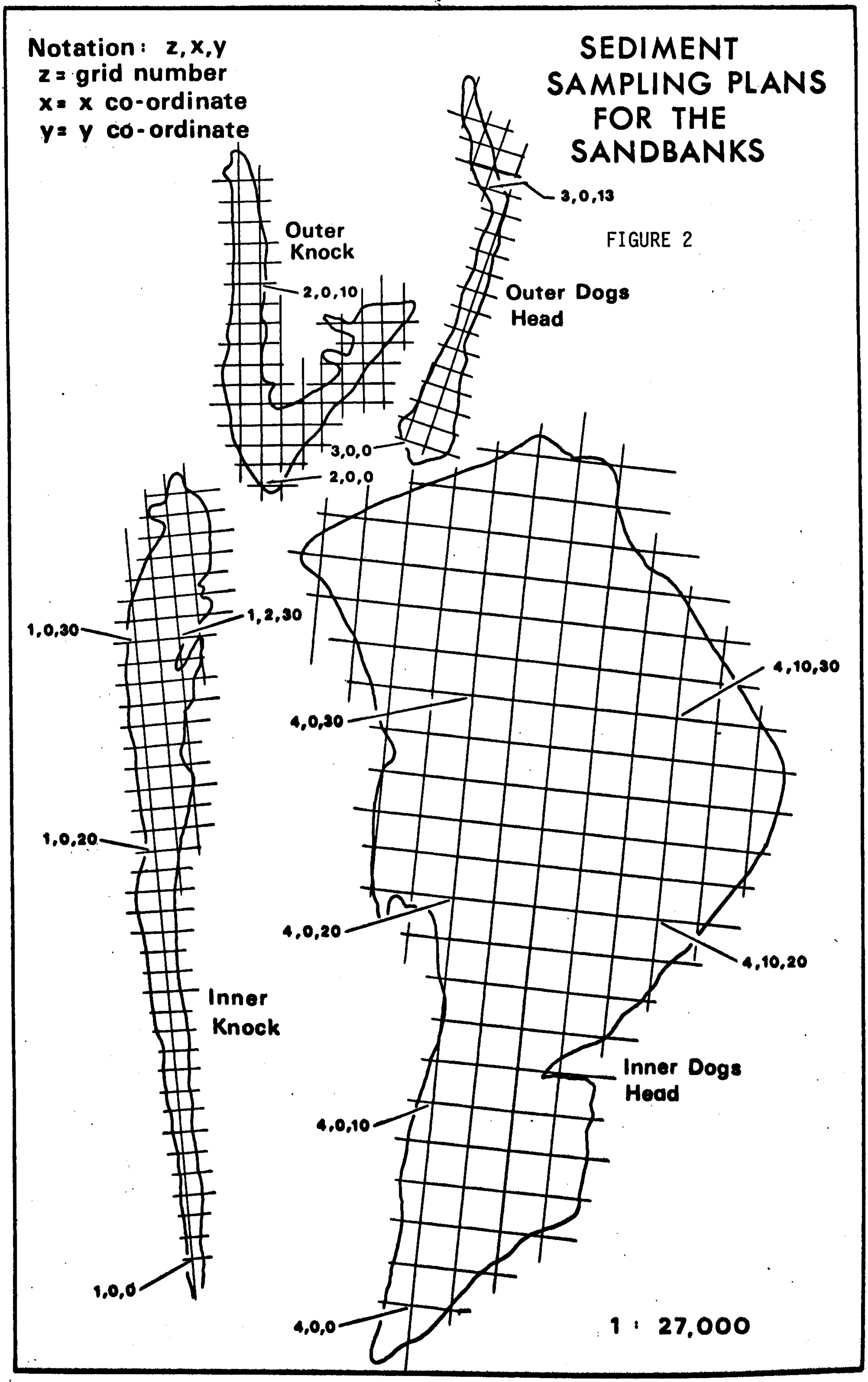
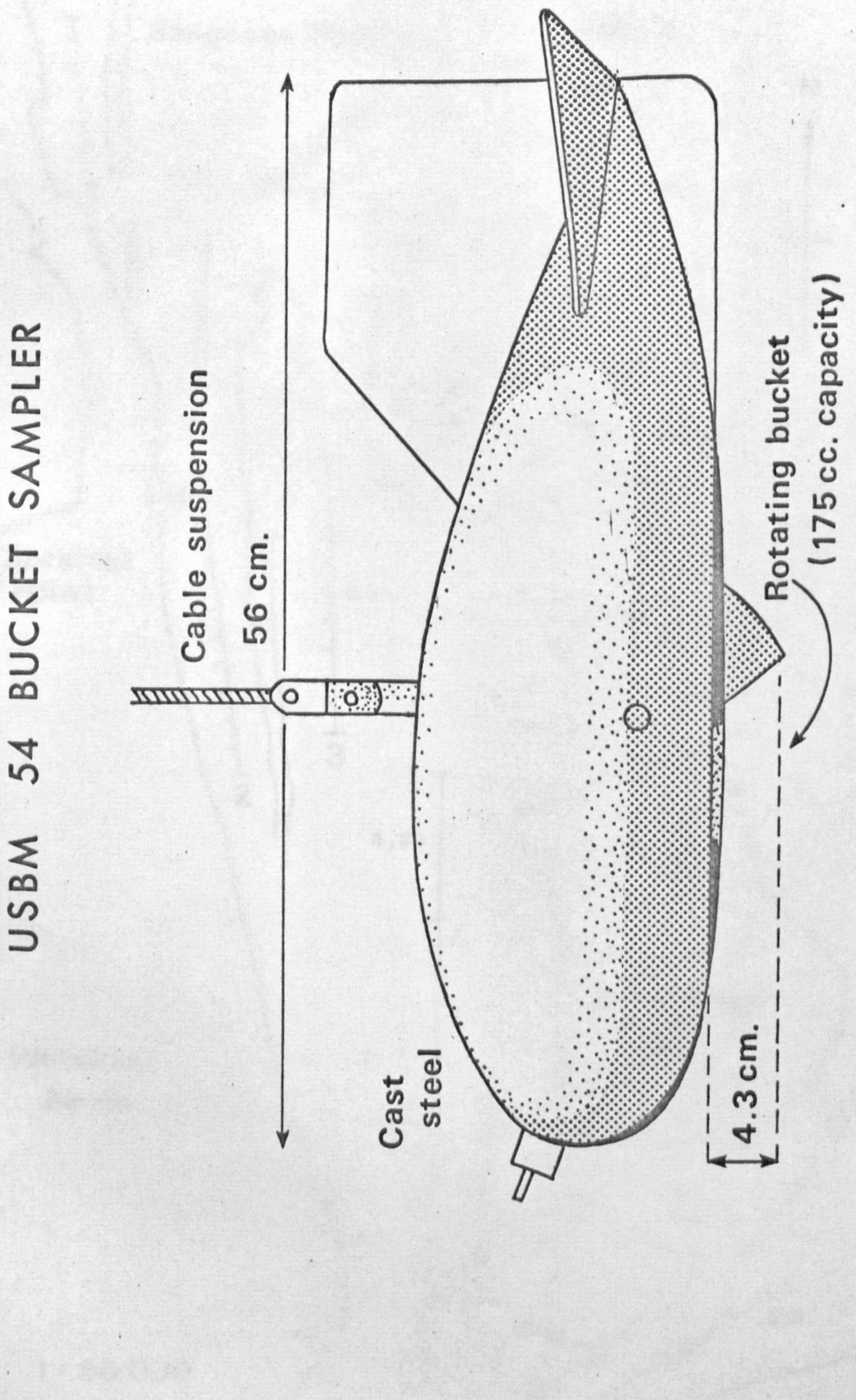
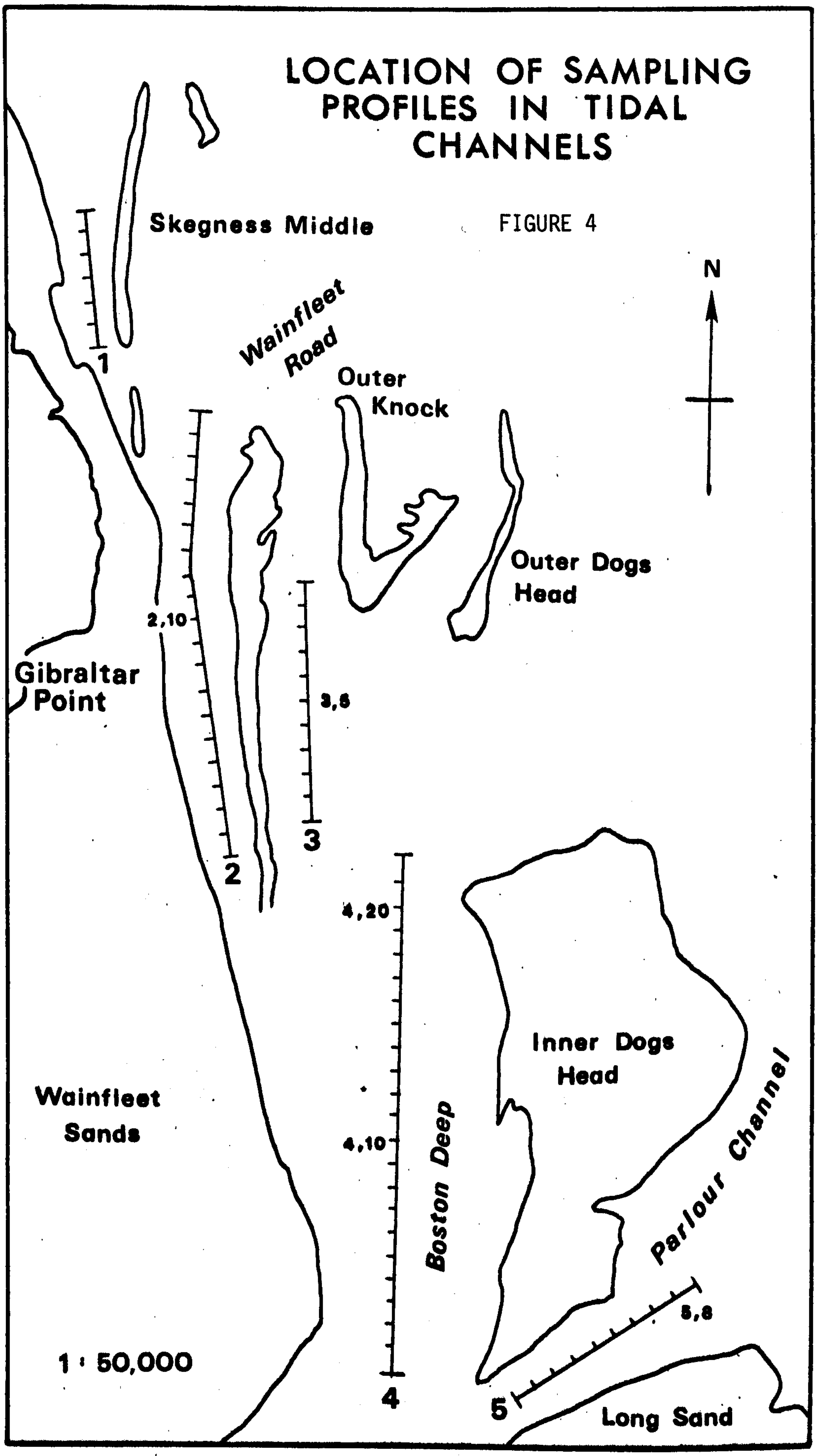

Notation: z,x,y
z= grid number
x= x co-ordinate
y= y co-ordinate
SEDIMENT SAMPLING PLANS FOR THE SANDBANKS
3,0,13
Outer Knock
2,0,10
Outer Dogs Head
3,0,0
2,0,0
1,0,30
1,2,30
4,10,30
4,0,30
1,0,20
4,0,20
4,10,20
Inner Knock
Inner Dogs Head
4,0,10
1,0,0
4,0,0
1 : 27,000

FIGURE 2

FIGURE 3


USBM 54 BUCKET SAMPLER
Cable suspension
56 cm.
Cast steel
4.3 cm.
Rotating bucket
(175 cc. capacity)


LOCATION OF SAMPLING PROFILES IN TIDAL CHANNELS
FIGURE 4
N
Skegness Middle
Wainfleet Road
Outer Knock
Outer Dogs Head
Gibraltar Point
Inner Dogs Head
Parlour Channel
Boston Deep
Wainfleet Sands
Long Sand
1 : 50,000
1
2
2,10
3
3,5
4
4,20
4,10
5
5,8

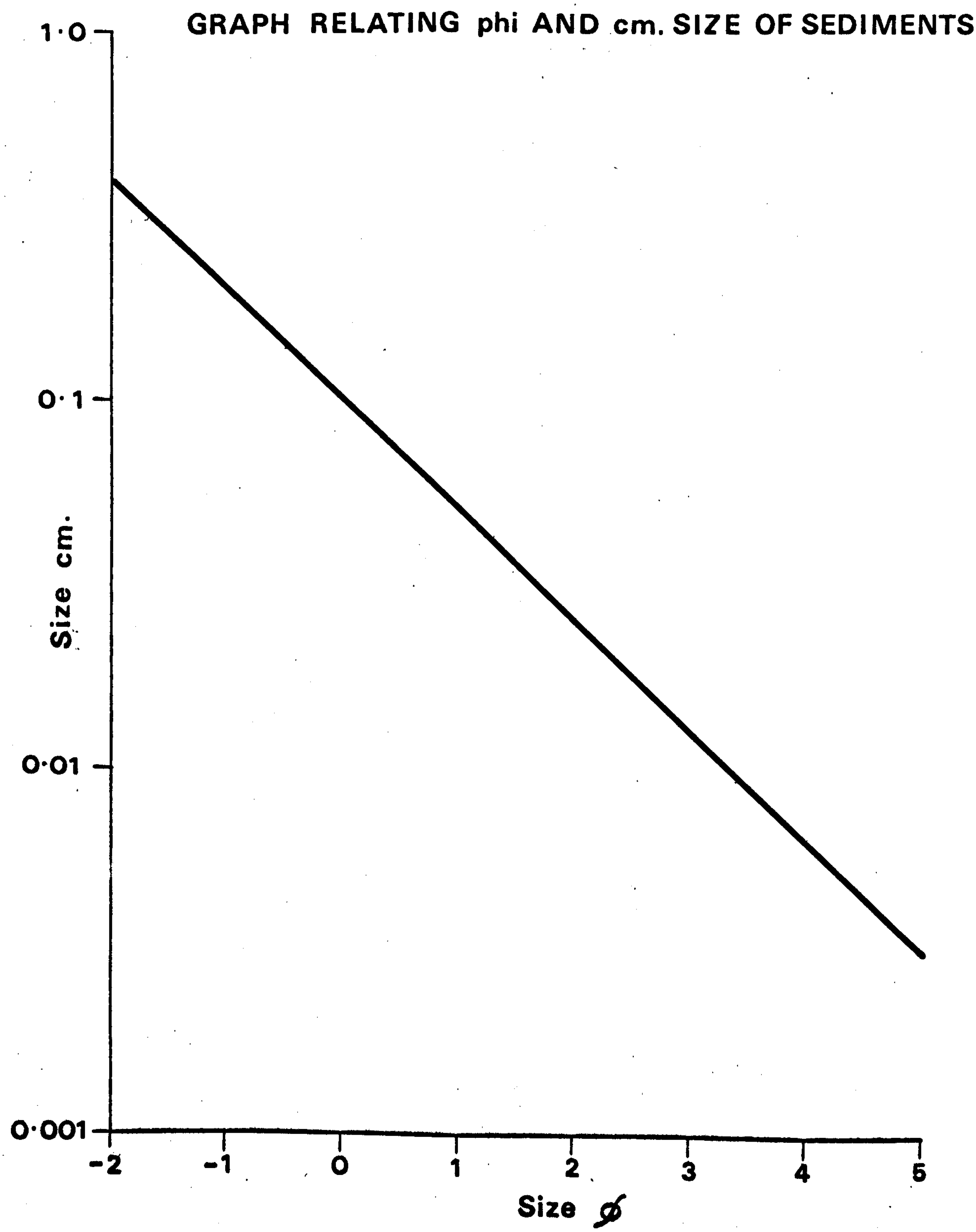
LABORATORY AND STATISTICAL PROCEDURES.

On return to the laboratory the samples were dried, weighed and mechanically analysed by dry sieving using a mechanical shaker for a period of 20 minutes. Sieves were used with apertures corresponding to the phi-scale (Inman, 1952) of logarithmic progression. A graph (Figure 5) is reproduced (after Inman, 1952) for conversion from phi-units to centimeter equivalents. The fraction of the sample retained in each sieve was weighed and recorded.

Data resulting from dry sieve analysis are usually displayed as a size-frequency curve on arithmetic probability paper. The moment measures of central tendency (the mean), standard deviation (sorting) and skewness are calculated from significant percentage coarser figures (King, 1966, p.279) read from the above curve and substituted in the formulae of Folk (1966) or Inman (1952). McCammon (1962) discusses the efficiency of the graphic methods of moment measures determination.

The major disadavantage of the graphic method of moment measure determination is that the discrete sampling process gives no information about the curve between sample points. Also, using most formulae the tails of the curve are ignored. Computer programmes have been published which take account of the total distribution. Collias et. al. (1963) published a programme which calculates moment measures based on the assumption that the weight in each phi interval is massed at the centre of that interval. Schlee and Webster (1965) published a programme which uses a continuous parabolic interpolation of the frequency curve. Errors can be introduced by this interpolation. Seward-

FIGURE 5



GRAPH RELATING phi AND cm. SIZE OF SEDIMENTS
1·0
0·1
0·01
0·001
Size cm.
-2
-1
0
1
2
3
4
5
Size ∅

Thompson and Hails (1973, p.168) published a formula which is claimed to overcome the difficulties encountered in the previously mentioned programmes. This formula, with minor modifications for programming purposes, was used as a basis of a computer programme written to determine the moment measures of sediment samples from the nearshore zone. The programme is capable of calculating any specified number of moments of distribution, but the first three moments of mean, standard deviation and skewness were selected for further study.

AREAL DISTRIBUTION OF SEDIMENT SIZE, SORTING AND SKEWNESS

For the purpose of mapping the areal distribution of size and sorting of sediments the descriptive classifications of Folk and Ward (1957) were employed. The relationships between the descriptive classifications and the numerical phi unit values of mean and sorting are as follows :-

Mean (Phi units)	Descriptive classification
-2.0 to -1.0	Granule
-1.0 to 0.0	Very coarse sand
0.0 to 1.0	Coarse sand
1.0 to 2.0	Medium sand
2.0 to 3.0	Fine sand
3.0 to 4.0	Very fine sand

Sorting (Phi units)	Descriptive classification
Less than 0.35	Very well sorted
0.35 to 0.5	Well sorted
0.5 to 1.0	Moderately sorted

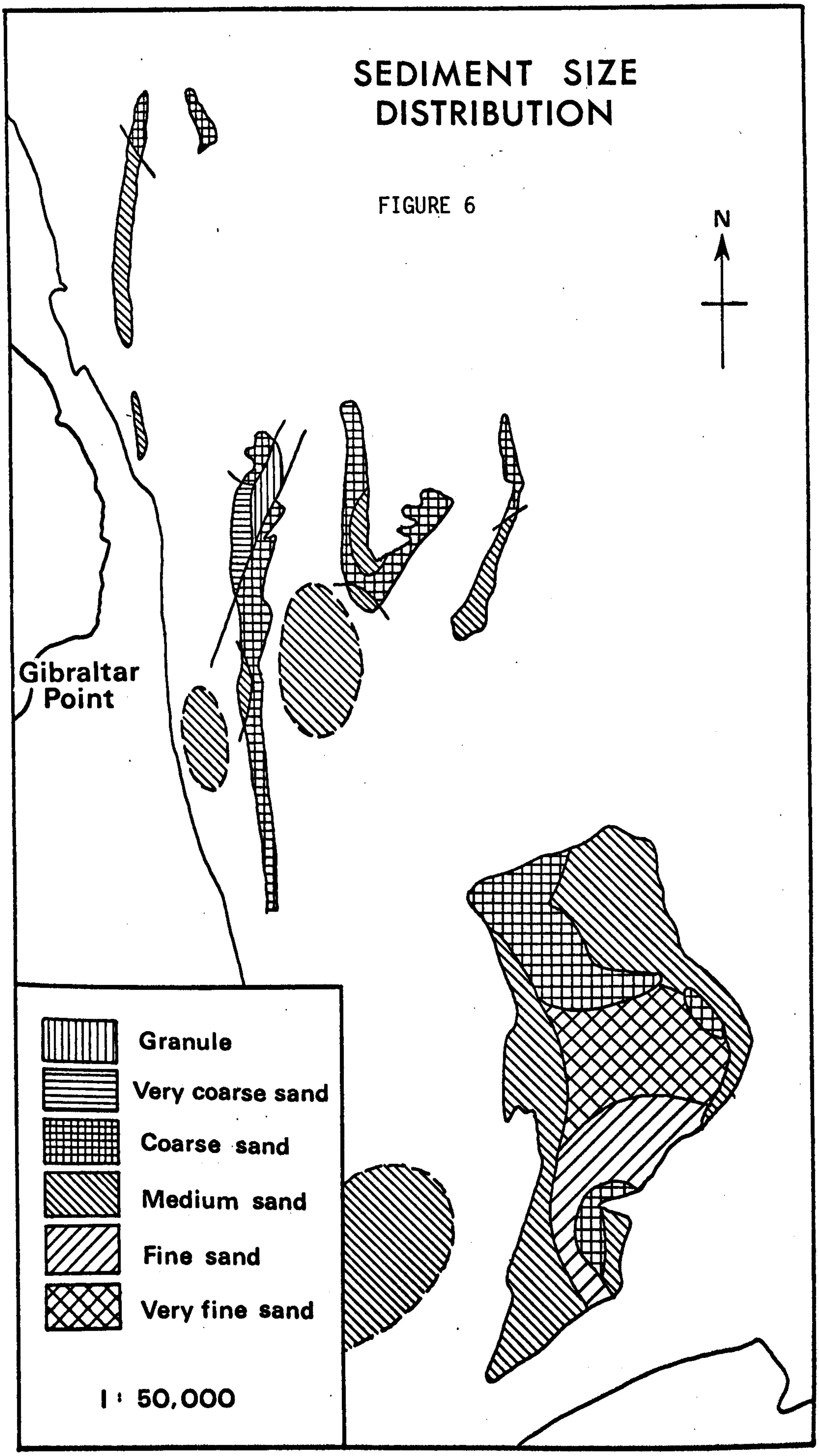
1.0 to 2.0	Poorly sorted
2.0 to 4.0	Very poorly sorted

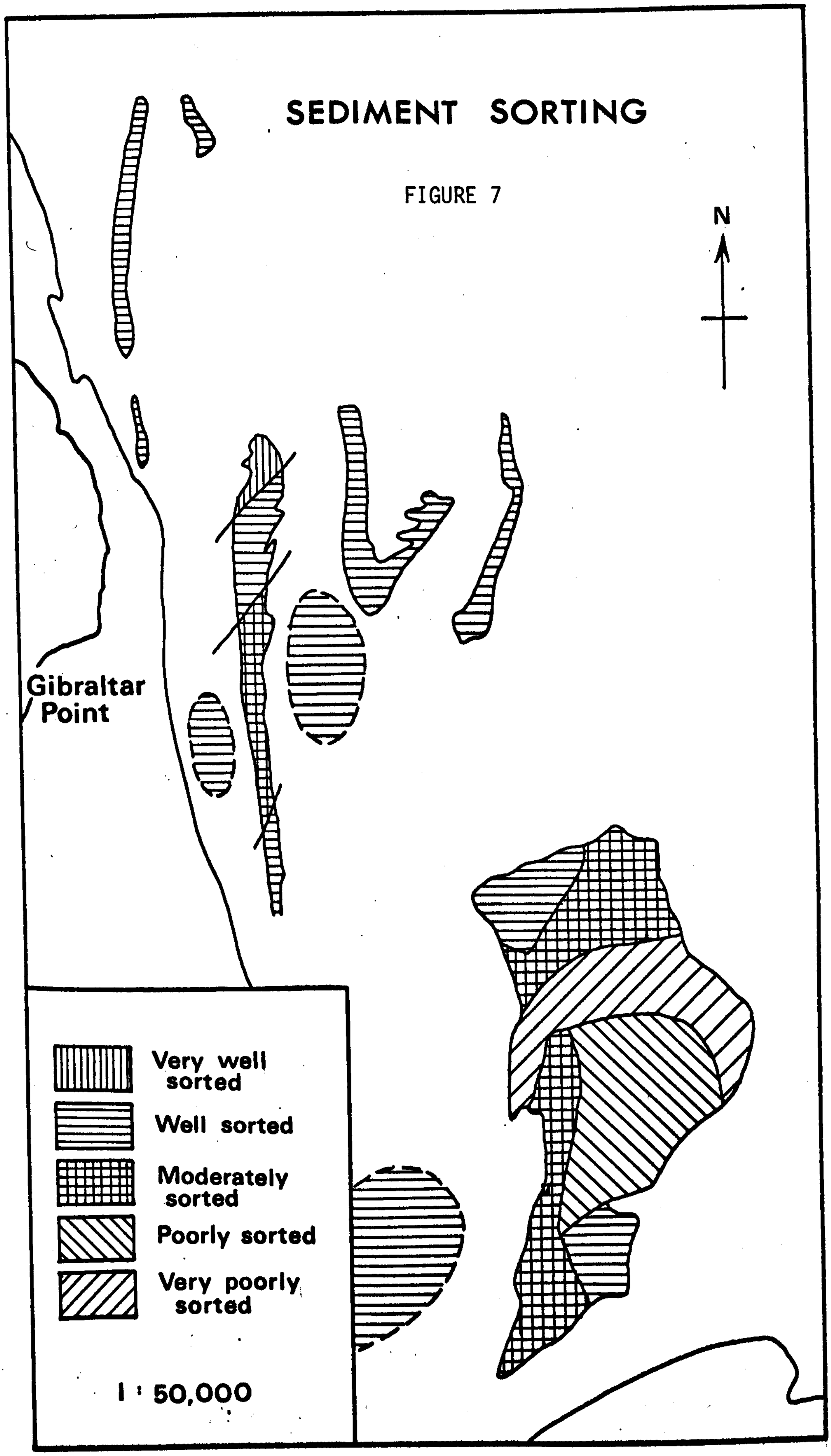
The criteria for mapping areas of sandbanks falling into particular categories of the above classifications were : (a) the majority of samples in a particular area should fall into the designated category and (b) the minority of samples should not contain any values of mean and sorting more than one category either side of the designated category. Based on these criteria the areas identified as belonging to particular mean and sorting categories are shown in Figures 6 and 7 respectively.

Mean sediment size of samples ranges from very fine on parts of the Inner Dogs Head to granule on parts of the Inner Knock. The frequency of occurrence of sediment sizes, expressed as a percentage of total sandbank area covered by sediment of a particular mean grain size, is as follows :- granule, 1.2%; very coarse sand, 2.0%; coarse sand, 29.1%; medium sand, 40.9%; fine sand, 11.4%; and very fine sand 15.4%. Medium and coarse sand together account for 70% of total sandbank area exposed at low water on spring tides.

Sorting of sediment samples ranges from very poorly sorted on parts of the Inner Dogs Head to very well sorted on parts of the Inner Knock. A total of 67% of the sandbank area exposed at low water on spring tides is covered by sand falling into the categories moderately to very well sorted.

Skewness of sediment samples was classified and mapped on a different basis from mean and sorting. The considerable variation in the value of skewness over small areal units and the range of variation of skewness values dictated the choice of a simple, four


SEDIMENT SIZE DISTRIBUTION
FIGURE 6
N
Gibraltar Point
Granule
Very coarse sand
Coarse sand
Medium sand
Fine sand
Very fine sand
1 : 50,000


SEDIMENT SORTING
FIGURE 7
N
Gibraltar Point
Very well sorted
Well sorted
Moderately sorted
Poorly sorted
Very poorly sorted
1 : 50,000

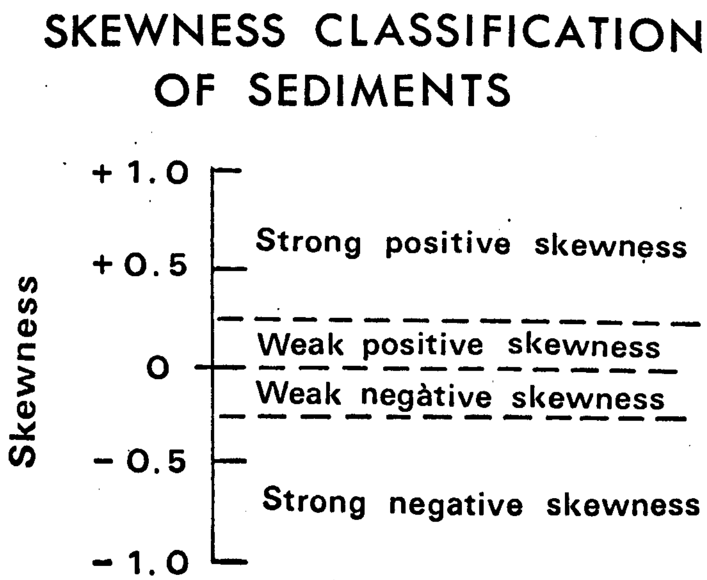
category, classification (Figure 8). For areas of sandbanks to be assigned to the categories of strong negative or positive skewness all values of skewness in these areas must be greater than 0.25 in a negative or positive direction respectively. Areas of weak positive skewness could contain both positively and negatively skewed samples but the positively skewed samples must be in the majority. Conversely, areas of weak negative skewness could contain both negatively and positively skewed samples but the negatively skewed samples must be in the majority.

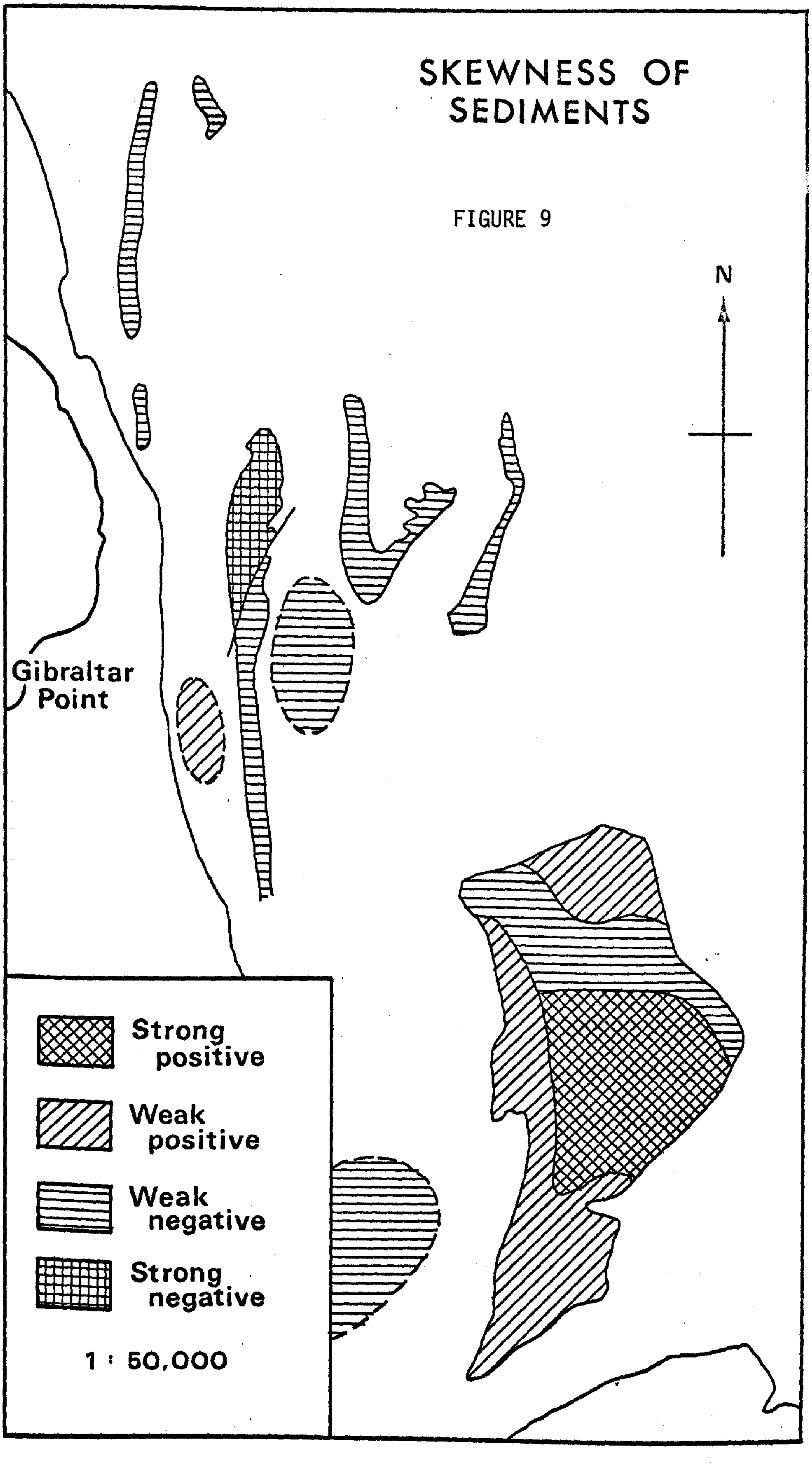
The areas identified as belonging to the skewness categories as defined above are shown in Figure 9 . The northern end of the Inner Knock is composed of strong negatively skewed sediments (6% of sandbank area). The remaining parts of the Inner Knock, the Outer Knock, the Skegness Middle, the Outer Dogs Head and a band across the northern parts of the Inner Dogs Head have weak negatively skewed sediment (37% of sandbank area). The northern tip, the southern tip and the western side of the Inner Dogs Head have weak positively skewed sediment (26% of sandbank area). Of the three patches of sand located in the channels that in the Wainfleet Swatchway contains sediment which is weak positively skewed whereas the two patches in the Boston Deep have weak negatively skewed sediment.

DISCUSSION

Stride (1963) inferred sediment movement direction in the North Sea based in part on the progressive decrease in mean grain size of sediments along transport paths. Bottom sediments were found to change systematically from medium sand to mud in a northerly direction over a distance of 200 km. along a section off the coast of

FIGURE 8


SKEWNESS CLASSIFICATION OF SEDIMENTS
Skewness
+1.0
+0.5
0
-0.5
-1.0
Strong positive skewness
Weak positive skewness
Weak negative skewness
Strong negative skewness


SKEWNESS OF SEDIMENTS
FIGURE 9
N
Gibraltar Point
Strong positive
Weak positive
Weak negative
Strong negative
1 : 50,000

Denmark. No such systematic change in sediment size is evident in the study area. The total distance north to south in the study area is 12.5 km. and systematic variation in sediment size is either not present, due to a lack of differentiation along relatively short transport paths, or is masked by variations of sediment size related to the variations in power of the tidal currents responsible for the entrainment, transport and deposition of sediment in the area.

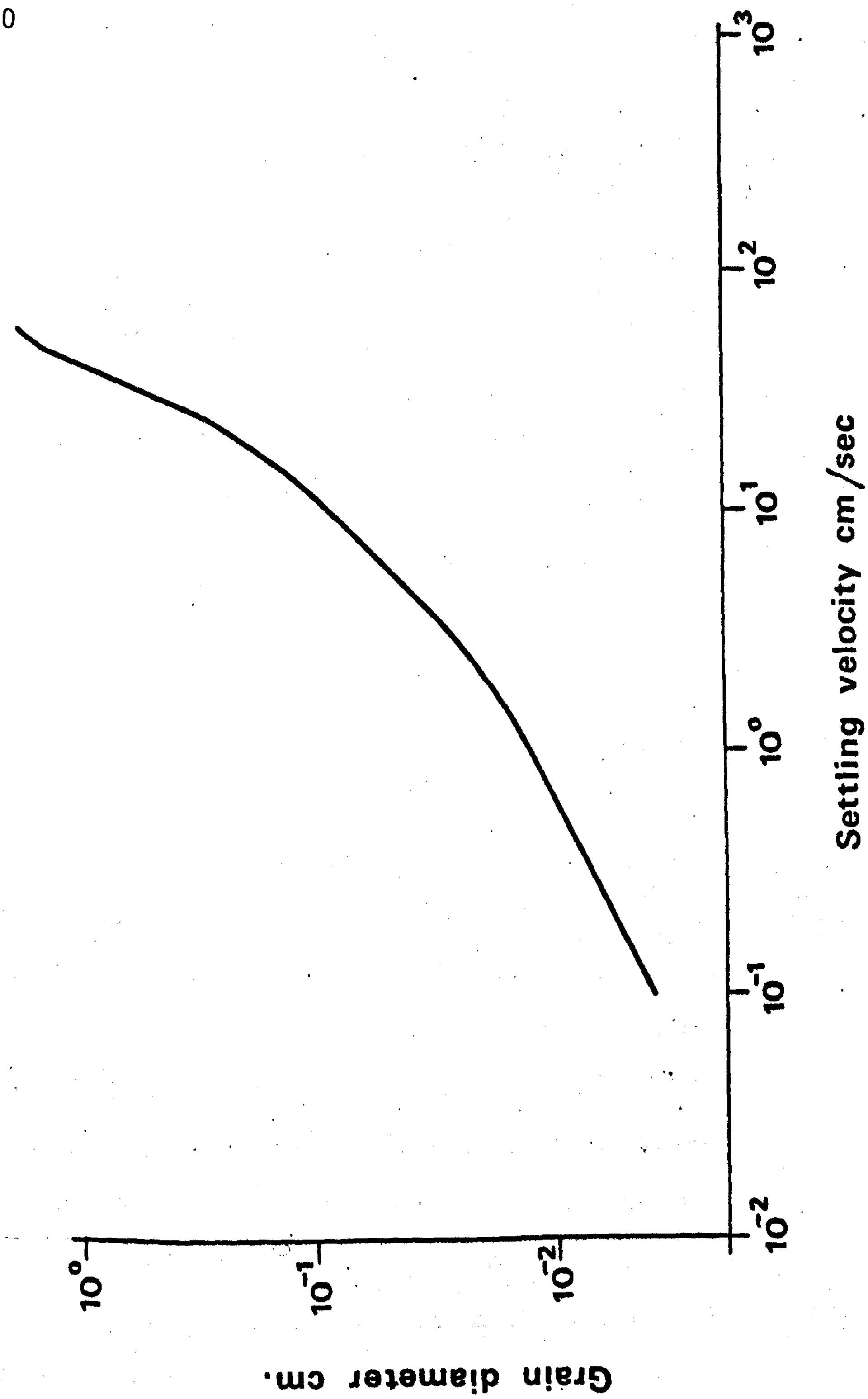
The areal distribution of mean sediment size on the sandbanks is the end product of the entrainment, transport and deposition of sediment by tidal currents. The pattern of sediment distribution mapped in Figure 6 will reflect the forces operating at the time of deposition of sediment prior to the emergence of the sandbanks on a falling tide. Empirical relationships between sediment size and the force applied by flowing water necessary to initiate sediment movement and the power of water flow and transport rates of sediment are available in the literature (Chapter 6, this thesis). Little is known, however, regarding the physical processes of deposition of sand grains in moving water.

Individual sand grains, once entrained by moving water, have a tendency to return to the depositional surface which is usually expressed in terms of a settling velocity. Raudkivi (1967) suggested that settling velocity is a function of size, shape and density of sand grains and the viscosity and turbulence intensity of the water through which the particle is falling. The concentration of particles in a water column can also effect the settling velocity of individual sand grains. The available theoretical and empirical information regarding settling velocities of sand grains in moving water with dispersed clouds of particles in suspension is very meagre, probably because observation of the process in operation is virtually impossible. Maude and Whitmore (1958) in a general theoretical study of sedimentation conclude that increased turbulence decreases settling velocity and increased concentration of sand grains in suspension increases the settling velocity of individual particles.

Most studies of the processes of sedimentation have concentrated on the settling velocity of individual grains in still water. Oliver and Ward (1959) considered the relationship between viscosity and settling velocity and concluded that settling velocity decreases as viscosity increases but not in a linear fashion. The relationship between grain size and the settling velocity of individual quartz sand grains in still water was studied by Pettyjohn and Christiansen (1948) and was summarised in graph form by Graf (1971) which is reproduced as Figure 10 . According to this graph the larger the grain the higher the settling velocity and therefore, the greater the tendency to return to the depositional surface. Since the tendency to return to the depositional surface is usually counteracted by the forces applied by moving water it follows that larger grains will be able to settle through higher velocity flows than smaller grains. Little is known about the intensity of turbulence in tidal flows but assuming the viscosity of the seawater, concentration of sand grains in suspension and grain density do not vary significantly in the study area the grain size of sediments deposited by tidal flows sould be an indirect measure of the power of such flows at the time of deposition of the sediments. A quantitative relationship between grain size and power of tidal flows at the time of deposition of sediment is not known but a qualitative statement that higher velocity tidal flows are

FIGURE 10

SETTLING VELOCITY FOR QUARTZ GRAINS IN STILL WATER



reflected in larger grain size is appropriate to the development of a sediment movement model.

Applying this argument to the study area two areas of sandbank have significantly different grain size properties than the remaining 70% of sandbank area, covered by medium and coarse sand, to be worthy of comment. At the northern end of the Inner Knock areas of granule and very coarse sand are found suggesting this is a location of relatively strong tidal currents compared with surrounding areas. In contrast the central area and the south eastern side of the Inner Dogs Head are covered with very fine sand and fine sand. Thin layers of mud, approximately 3 cm. thick, containing shell fragments were also noted in these areas during the collection of sand samples. The occurrence of fine sands and muds in close association suggest an area of relatively weak tidal current flow. The areas occupied by these sediments must be protected in some way from modification by stronger tidal currents associated with coarser sand on other parts of the sandbank. Morphological evidence of such protection will be given in Chapter 4.

As outlined in the introduction to this chapter sediment sorting is approximately proportional to the distance of transport of sediment by moving water and to the power of water flow. Again, probably due to the relatively short transport paths, no trends in sediment sorting can be discerned in the area. However, two areas again stand out as significantly different from the majority of moderately and well sorted sediment. The northern end of the Inner Knock exhibits very well sorted sediment again suggesting relatively strong tidal currents at this location. The central area of the Inner Dogs Head has poorly sorted sediment which confirms the relative weakness of tidal currents in this area. North of this area of poorly sorted sediments is an arcuate area of very poorly sorted sediments which in terms of grain size cannot be distinguisted from other parts of the sandbank. Since this area does not appear, on the basis of grain size, to be related to weak tidal currents it may be an area of meeting of two opposing tidal currents, one carrying very fine sand and fine sand from the south the other carrying medium and coarse sand from the north. In other words sediment of contrasting size are deposited in this arcuate band giving rise to very poorly sorted sediments. This hypothesis is again supported by evidence from sandbank morphology and bedforms in Chapter 4 and 5.

King (1964) collected and analysed nine sediment samples from the Wainfleet Swatchway, the Inner Dogs Head and the Outer Knock. Samples from the Wainfleet Swatchway had a negative skewness and those from the sandbanks a positive skewness which was thought to be characteristic of sediments deposited by unidirectional flow of tidal streams. Samples collected from a sandwave field on the Inner Dogs Head were found to have a slight negative skewness which was interpreted as representing a reworking of surface sediments by waves on the falling limb of the tidal cycle.

The analysis of sediments from the more comprehensive sampling plan presented in this thesis suggests a more complex interpretation is necessary, than that presented by King (1964), of the considerable variation of skewness shown by the clastic sediments which form the sandbanks. Furthermore, evidence from bedforms exposed at low water (Chapter 5, this thesis) suggests that modification by wave action is minimal particularly on the western, more sheltered, sides of the sandbanks. Skewness of sediments is, therefore, interpreted as an indicator of the relative energy levels of tidal currents associated with the transport and deposition of the sediments. As outlined in the introduction to this chapter negative skewness indicates an absence of fines, a quality characteristic of a more energetic environment. Conversely, positive skewness indicates a tail of fines, a characteristic of a quieter environment of deposition.

The northern end of the Inner Knock is the only part of the sandbanks where sediments with a strong negative skewness were found, and can be interpreted as an area of relatively high energy levels. In contrast the central area of the Inner Dogs Head is composed of sediments with a strong positive skewness suggesting relatively low energy levels. These conclusions confirm those deduced from mean grain size and sediment sorting. The remaining parts of the Inner Knock, the Outer Knock, the Skegness Middle and the Outer Dogs Head are formed of sediment with a weak negative skewness suggesting slightly higher energy levels than the northern tip and western side of the Inner Dogs Head where sediments have a weak positive skewness. This conclusion will be supported by evidence from bedforms in Chapter 5. The band of weak negative skewness across the northern end on the Inner Dogs Head is associated with the topographically highest parts of the sandbank (Chapter 4, this thesis). The relatively high energy conditions at this location compared with surrounding areas could be a response to shallower tidal flows.

Of the sediments sampled from the channels those from the Wainfleet Swatchway have a weak positive skewness compared with those from the Boston Deep which have a weak negative skewness. This suggests slightly higher energy levels in the Boston Deep, a conclusion which will be supported by evidence from tidal current measurement (Chapter 6, this thesis).

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CHAPTER FOUR

MORPHOLOGY OF THE SANDBANKS AND CHANNELS

THE PLAN SHAPE OF THE SANDBANKS

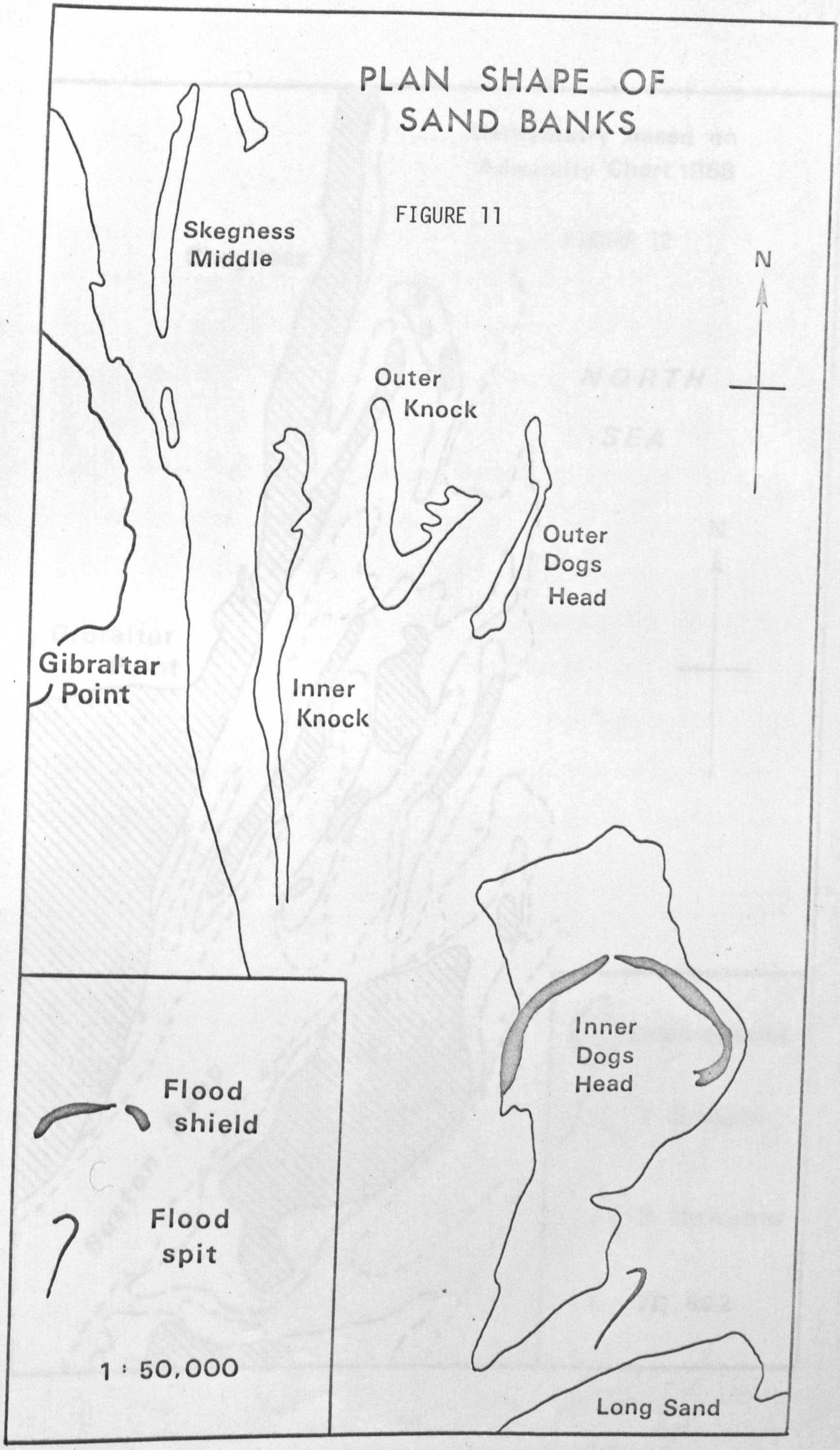
The plan shape of the sandbanks in the study area was obtained from an Admiralty Chart (Chart 108) and aerial photographs (Fairey Surveys Ltd., 1971). The shape of the sandbanks exposed at low spring tides is shown in Figure 11 and the bathymetry of the area based on Admiralty survey of 1956 is shown in Figure 12 . In terms of shape the sandbanks fall into two distinct categories :-

1. The Skegness Middle, Inner Knock, Outer Knock and Outer Dogs Head are comprised of, or form part of, linear ridges connected at one, or both, ends to adjacent sandbanks by a compressed sigmoidal apex. The Skegness Middle consists of a linear ridge approximately 3.5 km. in length connected by a northerly closing apex to a smaller eastern limb 0.5 km. in length. The Inner Knock, a linear ridge 4.5 km. in length, forms the western limb of a complex sandbank with apices closing alternately north, south and north. The first northerly closing apex connects the Inner and Outer Knock, the latter comprising the whole of the southerly closing apex. The Outer Dogs Head, a linear ridge 1.7 km. in length is connected to the Outer Knock by the second, eastern, northerly closing apex.

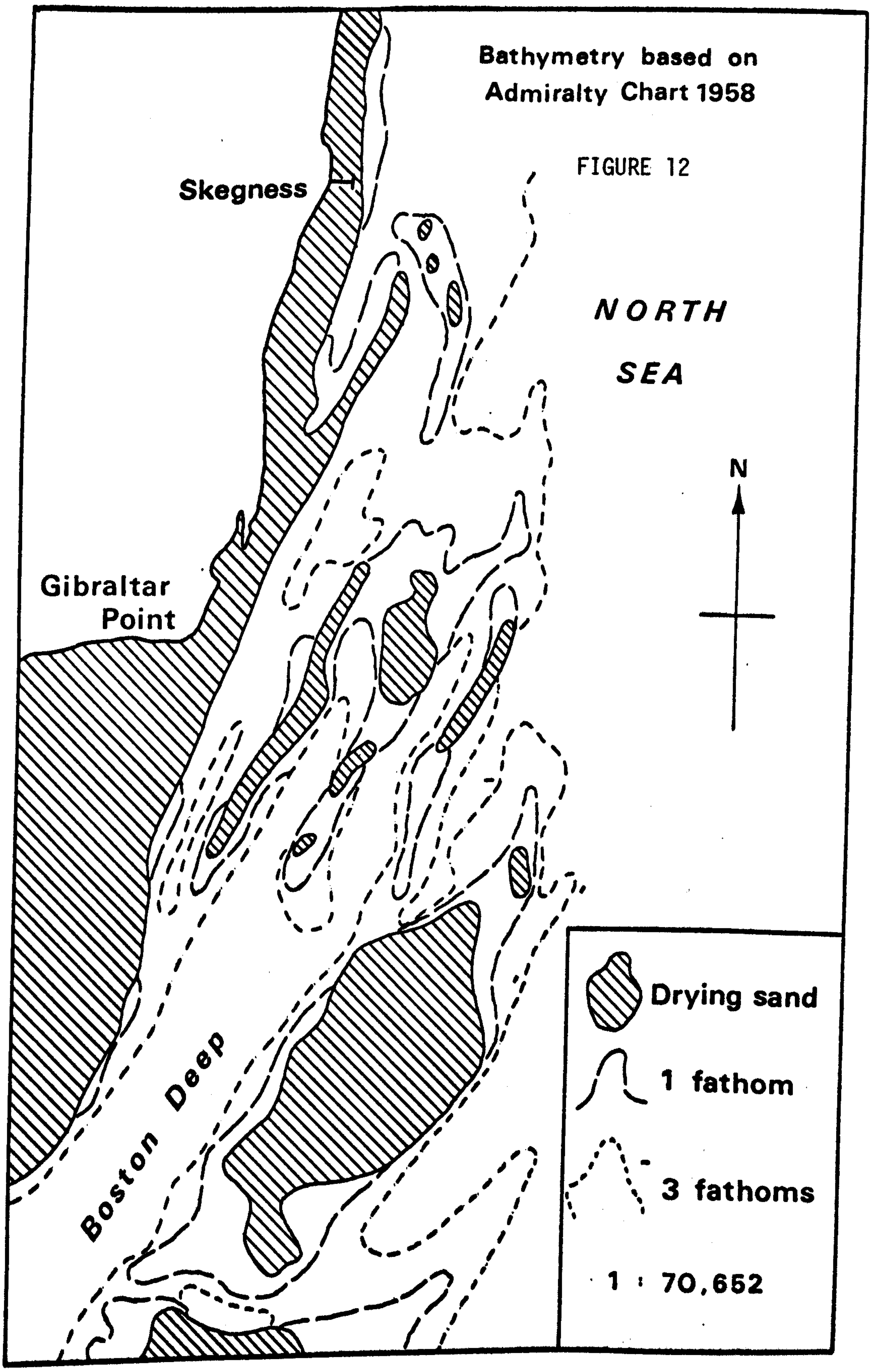
2. In contrast the Inner Dogs Head has a much greater areal extent than the other sandbanks in the area and is approximately triangular in plan shape.

THE SANDBANKS AND CHANNELS IN PROFILE

The cross-profiles of the sandbanks and channels were measured using boat mounted trace recording echo-sounder equipment. Profiles



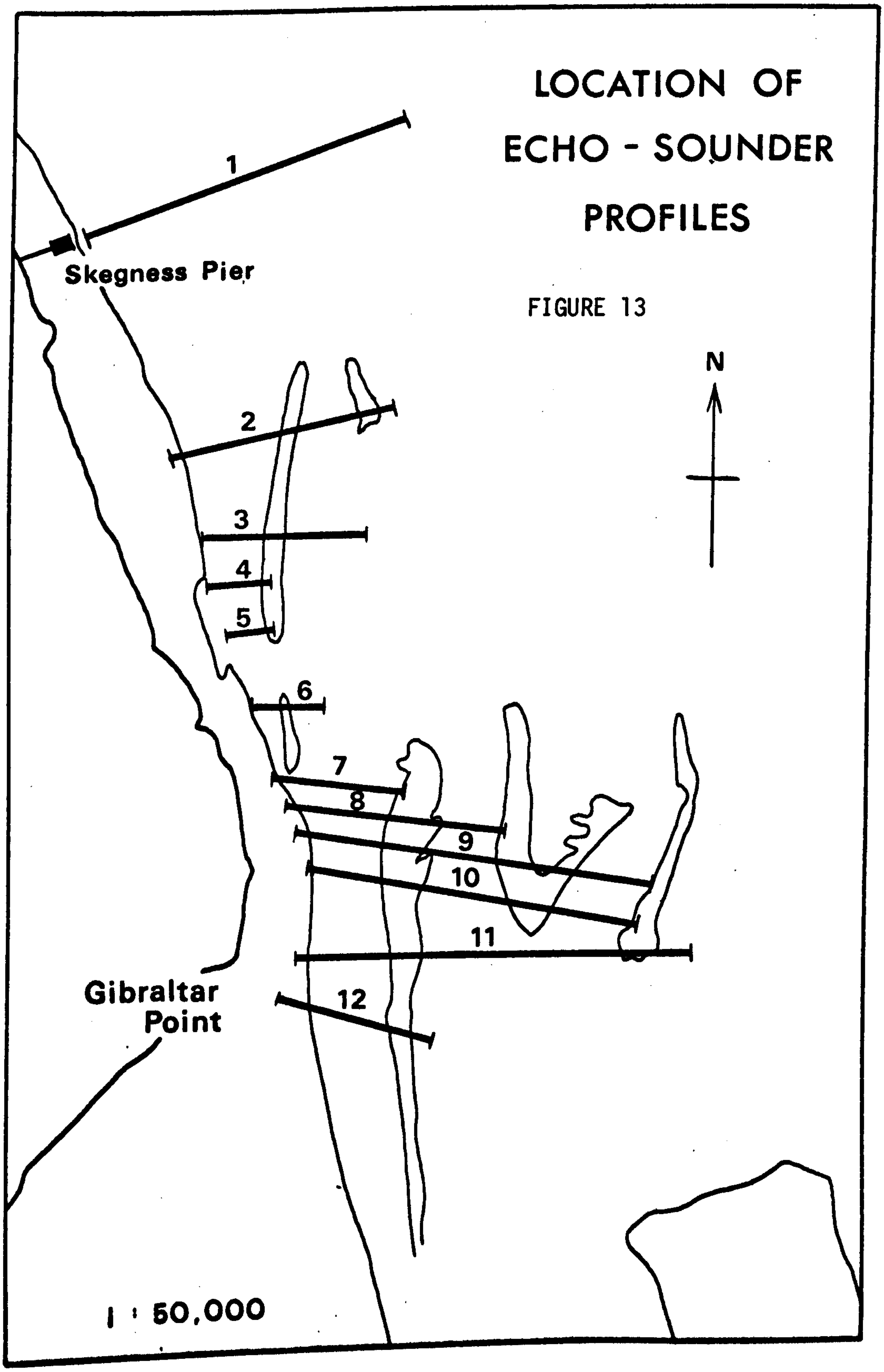
PLAN SHAPE OF
SAND BANKS
FIGURE 11
Skegness
Middle
N
Outer
Knock
Outer
Dogs
Head
Gibraltar
Point
Inner
Knock
Inner
Dogs
Head
Flood
shield
Flood
spit
1 : 50,000
Long Sand


Bathymetry based on
Admiralty Chart 1958
FIGURE 12
Skegness
NORTH
SEA
N
Gibraltar
Point
Boston Deep
Drying sand
1 fathom
3 fathoms
1 : 70,652

were run across the area at or near high water. In total 12 profile runs were made (Figure 13). All profiles were commenced in close proximity to a known location on the beach. A beach based radio operator was supplied with a prismatic compass and "talked" the boat along a pre-selected compass bearing. At the end of a profile run the boat position was fixed by means of a minimum of three compass bearings to landmarks on the shoreline. The engine speed of the boat was kept constant during all surveys. The two-way radio system of navigation was adopted to negate the possibility of boat drift due to wind or tidal currents.

The time at the beginning and end of each profile run was recorded to establish the height of the tidal plane during the survey. The height of the tidal plane was monitored continuously at Gibraltar Point during the periods of survey. All profiles were subsequently corrected to a standard height of 6.0 m. above local Admiralty Datum. The length of the echo-sounder trace was also corrected for variations in boat speed.

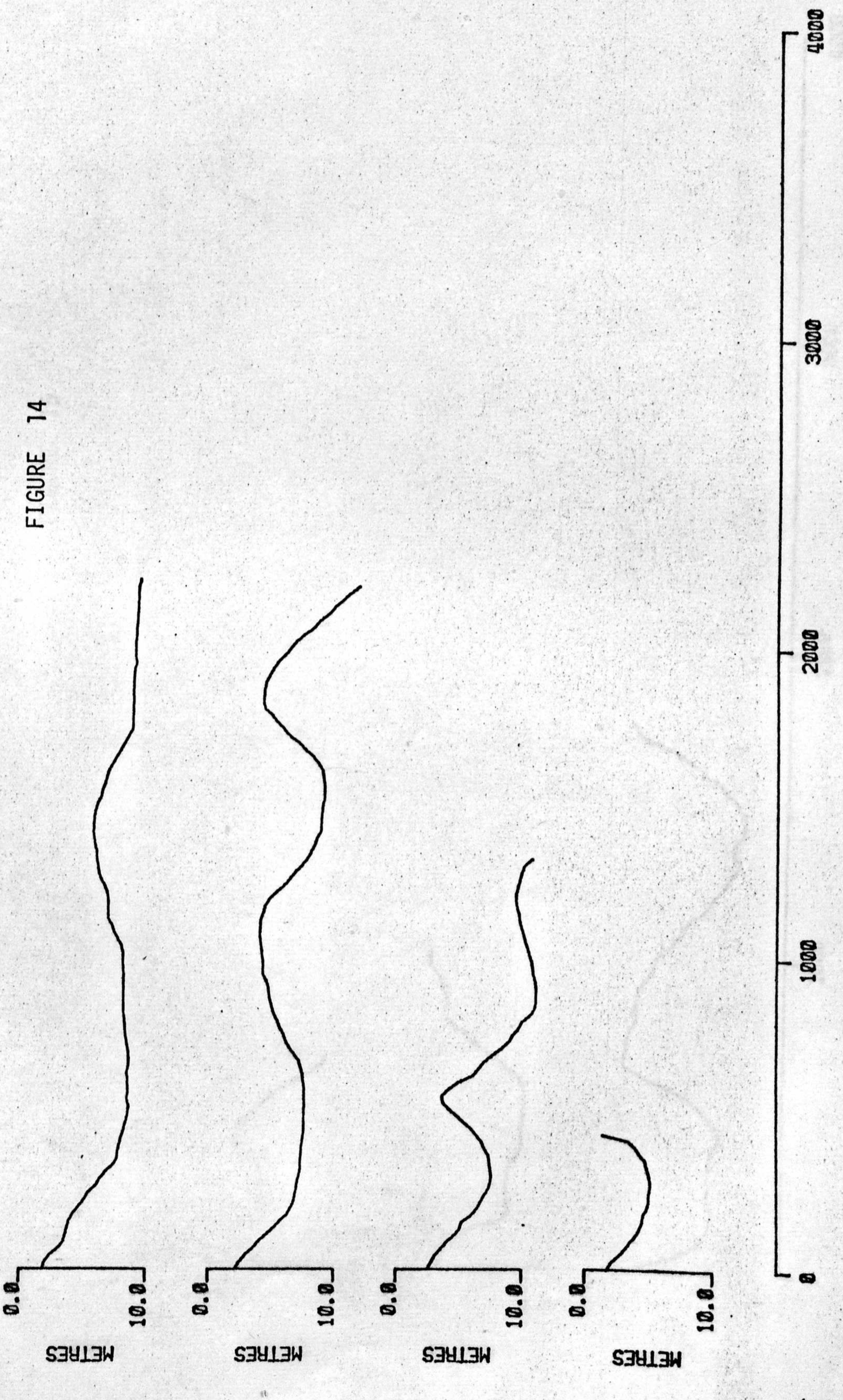
The profiles measured along the lines shown on Figure 13 are shown in Figure 14 to 16. Profiles 1 to 6 are taken across the Skegness Middle sandbank. The small rise in the middle section of Profile 1, taken seaward along the line of Skegness Pier, probably represents the northern extremity of the northerly closing apex of the sandbank. Profile 2 taken across both limbs of the sandbanks, show a marked asymmetry on the western limb, the eastern side being the steeper. The eastern limb is approximately symmetrical at this location. Profiles 3 to 6 illustrate the cross-sectional attributes of the western limb of the sandbank as it approaches the shoreline. At the location of Profile 3 the sandbank has lost the asymmetry


LOCATION OF
ECHO - SOUNDER
PROFILES
FIGURE 13
N
1
Skegness Pier
2
3
4
5
6
7
8
9
10
11
12
Gibraltar
Point
1 : 50,000

PROFILES 1 TO 4

VERTICAL EXAGGERATION X 40

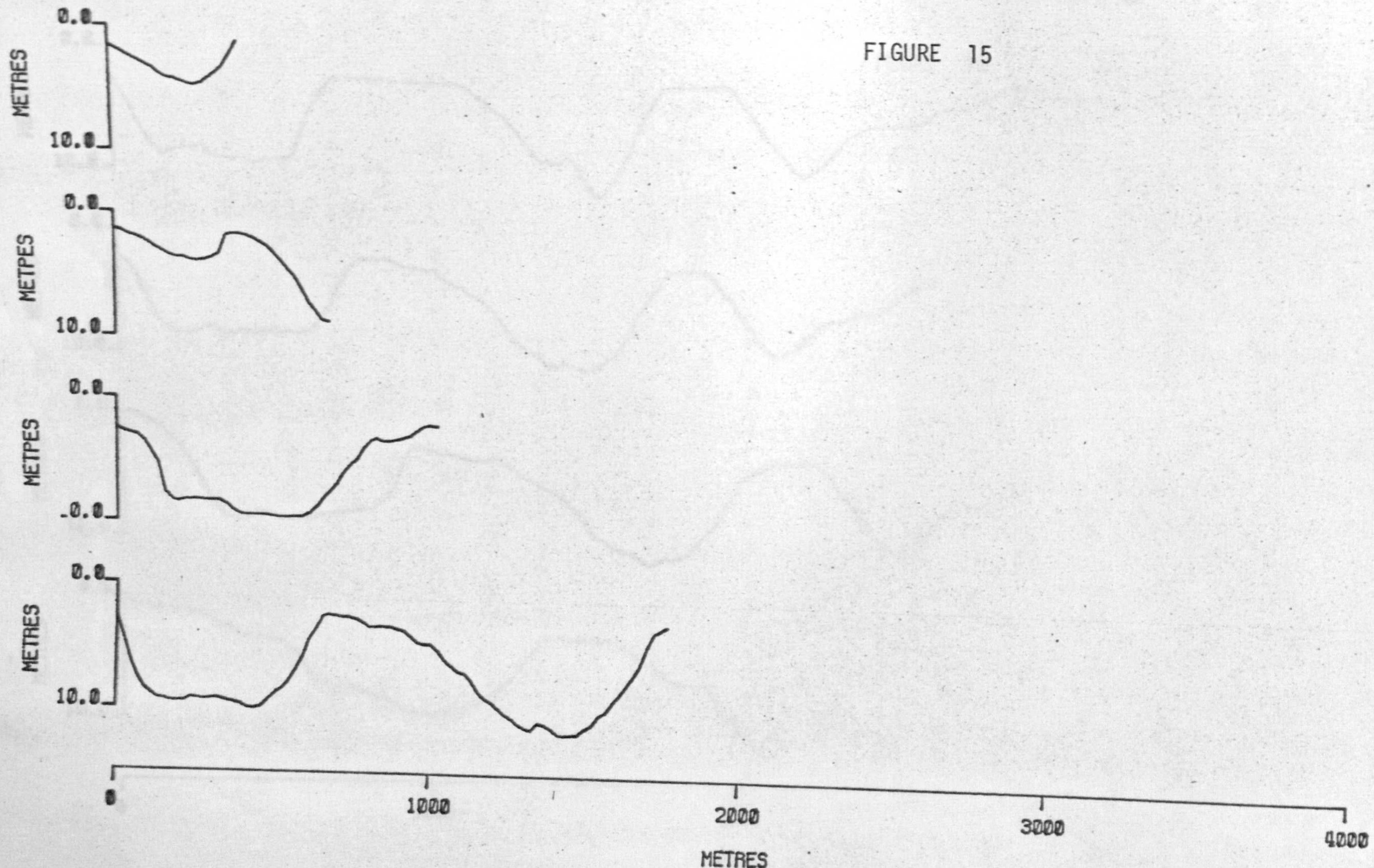
FIGURE 14



PROFILES 5 TO 8

VERTICAL EXAGGERATION X 40

FIGURE 15



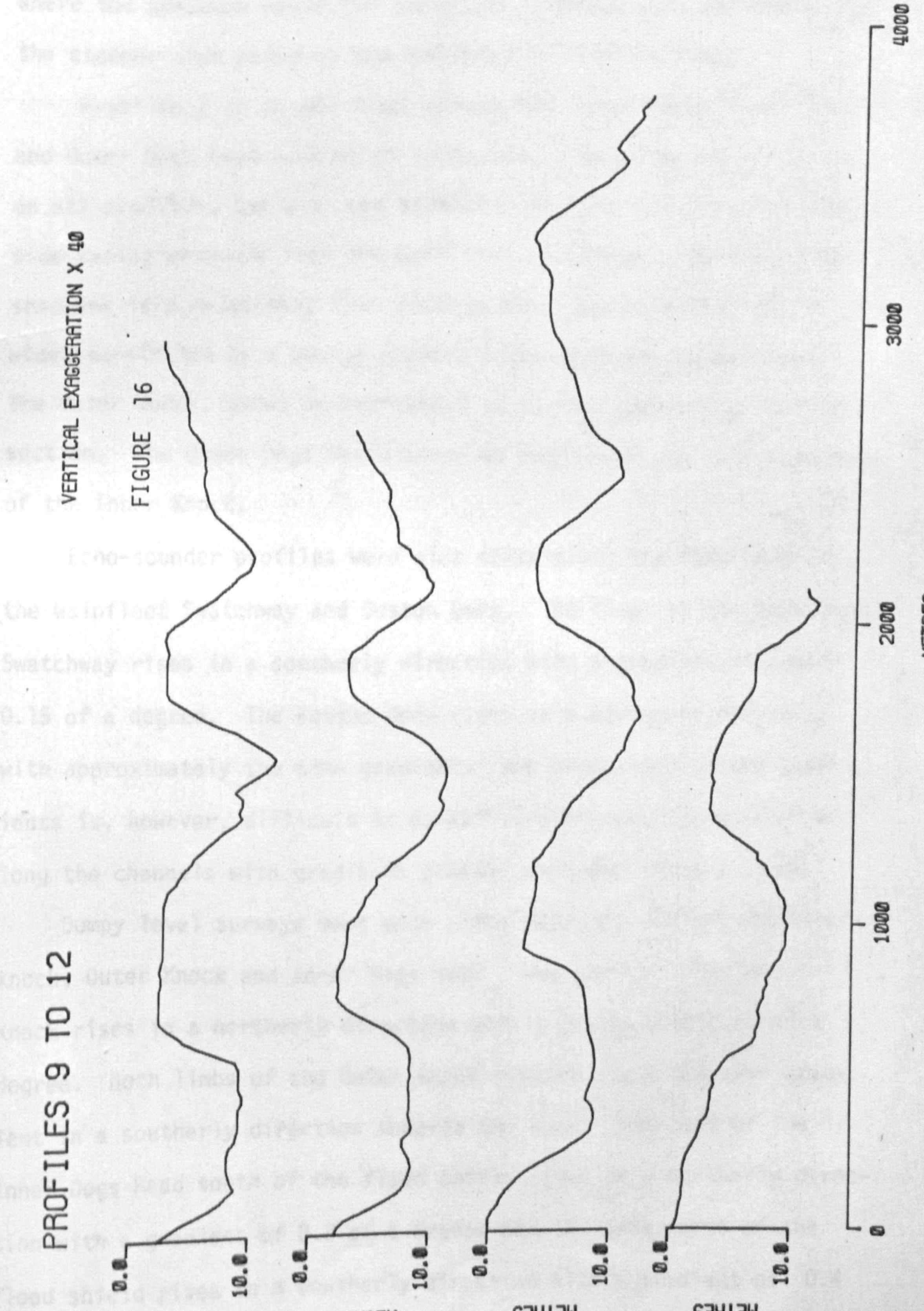

PROFILES 9 TO 12
VERTICAL EXAGGERATION X 40
METRES
0.0
10.0
METRES
0.0
10.0
METRES
0.0
10.0
METRES
0.0
10.0
0
1000
2000
3000
4000
METRES

FIGURE 16

shown in Profile 2 and is symmetrical. Profile 6, at the point where the sandbank meets the shoreline, shows a reversed asymmetry, the steeper side being on the shoreward or western side.

Profiles 7 to 12 are taken across the Inner Knock, Outer Knock and Outer Dogs Head complex of sandbanks. The Inner Knock, shown on all profiles, has a marked asymmetry in cross-section, the steeper side facing westward into the Wainfleet Swatchway. The top of the sandbank is a relatively flat plateau area, approximately 200 m. wide, terminated by a gentle eastern slope into the Boston Deep. The Outer Knock, shown on Profiles 9 to 11, is symmetrical in cross-section. The Outer Dogs Head, shown on Profile 11, is a mirror image of the Inner Knock.

Echo-sounder profiles were also taken along the long axes of the Wainfleet Swatchway and Boston Deep. The floor of the Wainfleet Swatchway rises in a southerly direction with a gradient of about 0.15 of a degree. The Boston Deep rises in a northerly direction with approximately the same gradient. The presence of these gradients is, however, difficult to establish since reversals occur along the channels with gradients greater than the overall trend.

Dumpy level surveys were made along the long axes of the Inner Knock, Outer Knock and Inner Dogs Head. The crest of the Inner Knock rises in a northerly direction with a gradient of 0.25 of a degree. Both limbs of the Outer Knock rise at about the same gradient in a southerly direction towards the apex. The part of the Inner Dogs Head south of the flood shield rises in a northerly direction with a gradient of 0.2 of a degree and the area north of the flood shield rises in a southerly direction with a gradient of 0.4 of a degree.

CLASSIFICATION OF SANDBANKS AND CHANNELS

Off (1963) described a large scale bedform, termed a tidal current ridge, which usually occurs in a rhythmic series of ridges parallel to tidal current flow and is found in shallow sea areas where the tide has undergone resonant amplification and there is a copious supply of sand sized sediment. These tidal current ridges appear to have three preferred locations for development. Firstly, tidal current ridges occur on continental shelf edges where they intercept oceanic tidal circulation (Swift, 1975). Secondly, they also occur off capes or promontories where they tend to be parallel to the coast (Caston and Stride, 1970). Thirdly, and more commonly, tidal current ridges are found in the mouths of estuaries or embayments and are generally parallel to the axis of the embayment and normal, or oblique, to the regional trend of the shoreline (Robinson, 1960). The Skegness Middle, Inner Knock, Outer Knock and Outer Dogs Head sandbanks fall into the latter category.

These large bedforms, or sandbanks, have been given several names in studies of their origin and mode of occurrence. Caston and Stride (1970) and Caston (1972), in studies of sandbanks off the Norfolk coast, preferred the term linear sandbank, avoiding the genetic connotation in the terminology of Off. Swift (1975) described these features as tidal ridges and Ludwick (1974) used the term zig-zag sand shoals in a study of bedforms in the entrance of Chesapeake Bay. The terminology of Off (1963), tidal current ridges, also used by Allen (1968), is adopted in this thesis.

Tidal current ridges found in the nearshore environment, as opposed to the continental shelf, appear to have two prominent features. As suggested in the terminology of Ludwick (1974), and first noticed by van Veen (1935, 1950), individual ridges are often connected at one, or both, ends to adjacent ridges by parabolic or compressed sigmoidal apices. Caston (1972) observed a marked cross-sectional asymmetry.

These two features are consistent with the interpretation of van Veen (1935) that the development of tidal current ridges is associated with the growth of ebb and flood tidal channels. The relationship between ridge and channel development was summarised by Robinson (1960). In areas where opposing ebb and flood tidal currents are found the momentum of flow of either tidal stream will cause a time lag in the reversal of flow direction. At the turn of the tide at low water, for example, the incoming flood stream would avoid the opposing ebb stream producing a mutually evasive flow and an interdigitation of tidal streams. The vector sum of flood and ebb stream velocities would, therefore, be areally variable and residual flows in either direction would occur during each tidal cycle. The boundaries between the interdigitations of flow residuals are areas of weaker currents due to the interaction between opposing flows. At these locations sediment is deposited forming the tidal current ridges. (Allen, 1968) Where a tidal stream is enclosed on both sides by opposing tidal streams the point where the enclosed tidal stream eventually losses momentum is the location for the deposition of the compressed sigmoidal link between two adjacent tidal current ridges. (Cloet, 1954)

The channels between tidal current ridges are classified in terms of the residual tidal flow associated with their development. Where the residual tidal flow is in an ebb direction in a particular channel, that channel is termed an ebb channel. Ebb channels often represent the seaward extension of river channels and commonly shallow in a seaward direction. A flood channel is one in which the tidal flow has a residual in the flood direction, and generally shallows in a landward direction.

The relative qualities, particularly density, and quantities of water associated with ebb and flood flows have implications regarding the nature of flow in the water column and the plan shape, depth and distribution of channels and sandbanks. In a study of the Merrimack estuary, Hartwell and Hayes (1969), using infra-red imagery and three dimensional surveys of water structure, noted vertical flow differentiation where denser saline water was flowing in a flood direction along the bottom of a channel while less dense water was flowing in an ebb direction on the surface. The same authors also noted maximum ebb velocities in the upper part of the water column and maximum flood velocities in the lower part of the water column. This vertical differentiation of flow could account for the relative deepness of flood channels compared with ebb channels in many estuaries.

Robinson (1960) noted the dominance of either ebb or flood channels related to the discharge of river water, the influx of seawater and the configuration of an estuary. In the Wash, a wide enclosed bay, where the influx of seawater is large compared with the discharge of river water flood channels are dominant. In contrast, the Humber, a long narrow estuary, has a relatively large discharge of river water and ebb channels are dominant.

The Inner Dogs Head, in contrast to the other sandbanks in the area, has a large areal extent and is approximately triangular in shape.

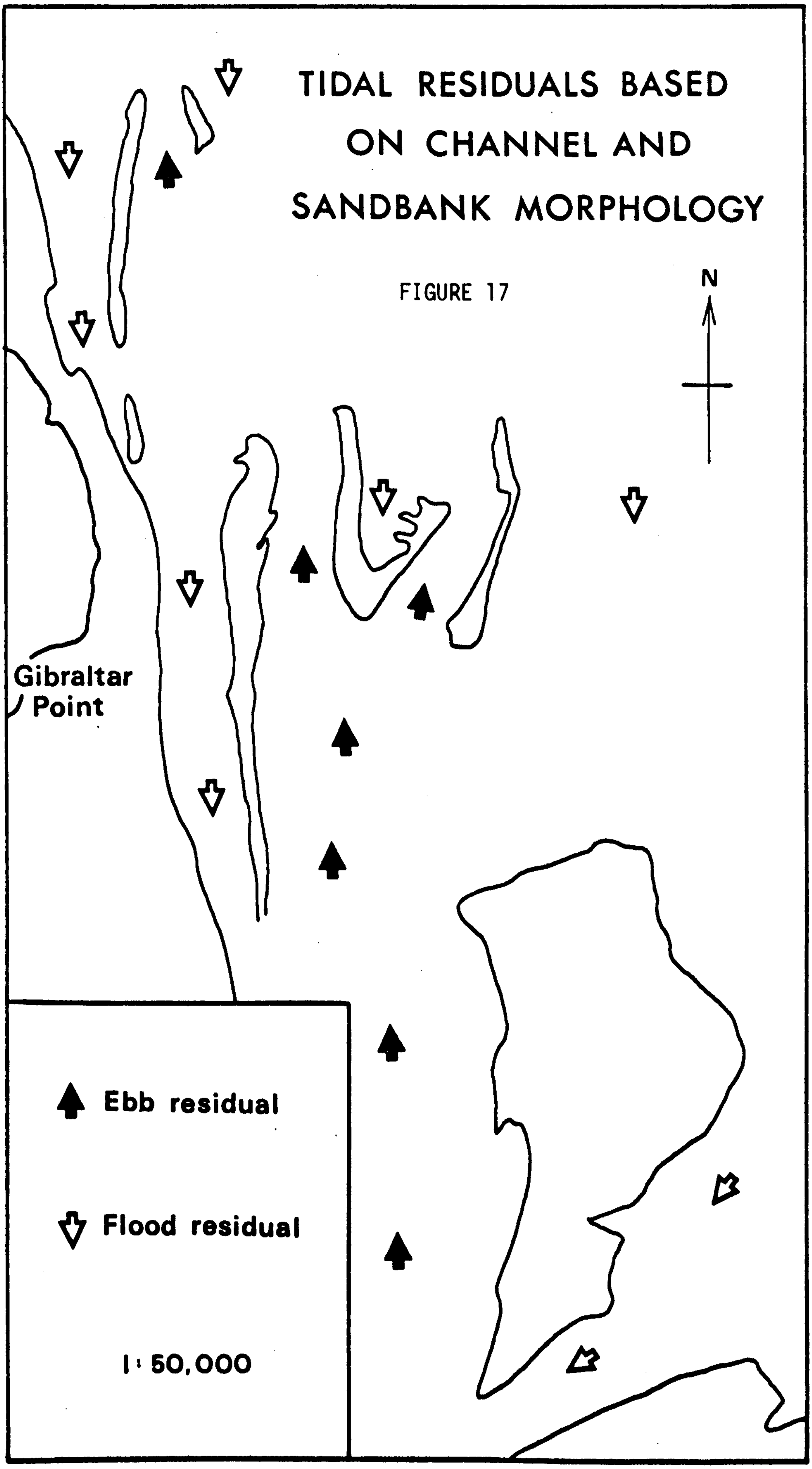
This type of sandbank is a common occurrence in the upper reaches of estuaries (Allen, 1970, p.179). Hayes (1969), in a study of New England estuaries classified these sandbanks as tidal deltas. Depending on the currents responsible for their formation these features can be subdivided into ebb and flood-tidal deltas. From evidence of bedforms (Chapter 5, this thesis) and the fact that the apex enclosing the long axis of the sandbank points landward, that is into ebb currents, the Inner Dogs Head is classified as an ebb-tidal delta.

Two more features, commonly associated with tidal deltas, find morphological expression on the Inner Dogs Head. Attached to the edge of the ebb-tidal delta and protruding into the Parlour Channel is a small spit (Figure 11). The orientation of the long axis of this spit is in sympathy with flood tidal currents in the Parlour Channel and following the terminology of Hayes (1969) it is classified as a flood spit. Approximately two-thirds of the distance along the long axis of the ebb-tidal delta from the southern extremity is a topographically high semi-circular ridge which extends across the whole breadth of the sandbank (Figure 11). This type of feature has been classified by Hayes (1969) as a flood shield. The relationship between shields and tidal currents is similar to that associated with the development of the compressed sigmoidal apices of the tidal current ridges. They are null points at the meeting of ebb and flood tidal currents and, therefore, zones of deposition of sediment. The term shield is derived from the fact that once these features have formed they offer protection to the areas they enclose from modification by flood tidal currents, in this case the southern two-thirds of the Inner Dogs Head.

DISCUSSION

Robinson (1964), in a study of sediment supply and coastal changes on the Lincolnshire Coast, classified the tidal channels in the nearshore zone near Gibraltar Point, on the basis of morphology, in a way that is in sympathy with the findings of the present study. The Boston Deep, which shallows in a northerly direction and is enclosed at the northern end by the Inner Knock, Outer Knock and Outer Dogs Head sandbank complex, is an ebb channel. This channel and the enclosing sandbanks, including the Inner Dogs Head on the eastern side of the channel, are enclosed on either side by flood channels. The southern end of the Wainfleet Swatchway shallows in a southerly direction on the western side of the Inner Knock and the Parlour Channel, on the eastern side of the Outer Dogs Head and Inner Dogs Head also shallows in a southerly direction. Further evidence of the flood dominance in the Parlour Channel is the flood spit. The northern end of the Wainfleet Swatchway, enclosed by the limbs of the Skegness Middle is an ebb channel. The channel between the western limb of the Skegness Middle and the shoreline closes in a southerly direction and is classified as a flood channel. The small channel between the southerly closing limbs of the Outer Knock is also a flood channel, developing in the nose of the parabola at the northern end of the Boston Deep. This classification of tidal channels in the study area is summarised in Figure 17.

Several authors, including Cloet (1954), Robinson (1960) and Ludwick (1974), have suggested that the residual of tidal flow associated with either ebb or flood channels must be reflected in the net movement of sediment in these channels. Applying this arqument


TIDAL RESIDUALS BASED ON CHANNEL AND SANDBANK MORPHOLOGY
FIGURE 17
N
Gibraltar Point
Ebb residual
Flood residual
1 : 50,000

to the study area, sediment movement in the Boston Deep and the northern end of the Wainfleet Swatchway should be in a northerly direction. Sediment movement in the southern part of the Wainfleet Swatchway, the Parlour Channel, the channel between the Skegness Middle and the shoreline and the channel between the limbs of the Outer Knock should be in a southerly direction.

Caston (1972) drew attention to the cross-sectional asymmetry of tidal current ridges as evidence of sediment movement direction. This study, of sandbanks off the Norfolk coast, suggested that tidal currents and associated sand streams on both sides of a sandbank are progressively deflected towards the crest of the sandbank, which becomes a zone of convergence and sediment deposition. The asymmetry results from the relative strength of the opposing tidal streams and the amount of sediment carried by these tidal streams. The stronger tidal current, or the one carrying the larger amount of sediment, will transport and deposit sand on a gently rising slope, the movement of sand being obliquely upslope. The weaker tidal current, or the one carrying smaller amounts of sediment, will deposit sand on the steeper slope. This steeper slope may also be partly related to the downslope dispersion of sediment being carried up the gentler slope and moved over the crest either by tidal currents or wave action. This process could explain the cross-stratification dipping down the steeper slope noted by Houbolt (1968) on the Well Bank off the Norfolk Coast. The asymmetry of tidal current ridges, therefore, represents a dominant movement of sediment obliquely up the gentler slope towards the direction of the steeper slope.

Applying this theory to the tidal current ridges in the study area, and ignoring for the moment the southerly closing apex of the

Outer Knock, it would appear that the ebb residual in the Boston Deep is stronger than the flood residual on either side and that sediment is transported up the gentler slopes of the Inner Knock and Outer Dogs Head from the Boston Deep in an approximately north-westerly and north-easterly direction respectively. The strength of the ebb residual in the Boston Deep and the associated sediment transporting capacity is further emphasised by the fact that over two-thirds of the area of the Inner Dogs Head is dominated by ebb tidal currents.

The Outer Knock, which is symmetrical in cross-section, has steep slopes on either side. This configuration could represent movement of sediment, by a flood residual, from the centre of the channel enclosed by the two limbs of the sandbank in a south-westerly direction on the western limb and a south-easterly direction on the eastern limb. At present, however, this southerly movement of sand is small when compared with the opposing movement in the Boston Deep.

The Skegness Middle sandbank presents a similar, but slightly more complex, picture. The western limb of this sandbank shows a reversal of asymmetry. At the southern end the dominant movement of sediment is probably from the south-east related to the ebb residual in the northern part of the Wainfleet Swatchway. At the northern end of the western limb, however, movement is probably in the opposite direction, that is from the north-west, and here related to the flood residual in the channel between the sandbank and the shoreline. The central symmetrical section of the sandbank represents a balance between sediment movement from the channels on either side.

In summary, evidence from the morphology of sandbanks and channels suggests a dominant northerly movement of sediment associated with a relatively strong ebb residual in the Boston Deep. Less significant southerly movements of sediment probably occur in the two flood channels enclosing the Boston Deep.

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CHAPTER FIVE

BEDFORMS

The relationship between bedforms, fluid motion and sediment movement has been expressed by Allen (1974) as follows :- "Natural sedimentary systems are process-response systems in which hierarchical configurations on the sedimentary surface (bedforms) are given character, maintained and translated because some of the energy supply is expended, that expenditure resulting in material transfers and transports". The various attributes of this system, and to a lesser degree the relationships between these attributes, have been the basis of extensive study during recent years. The purpose of this chapter is to exploit these relationships for the advancement of the sediment movement model.

CLASSIFICATION OF BEDFORMS

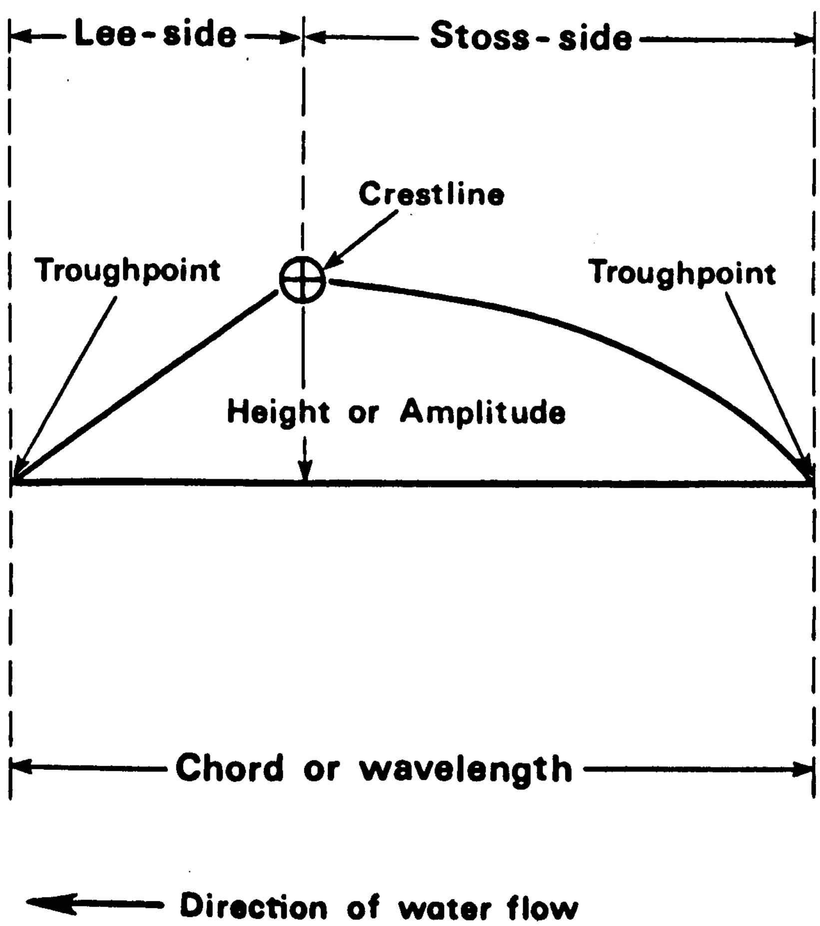
Bedforms are usually described and classified in terms of their physical dimensions parallel to water flow, that is in vertical profile, and morphology perpendicular to water flow, the trace of the crestline.

The important features of bedforms in vertical section are shown in Figure 18 . The height or amplitude is the vertical interval between the points of maximum and minimum elevation and the chord, or wavelength, is the horizontal distance between trough-points. The slope which dips up-current is known as the stoss-side and experiences erosion to a greater or lesser degree. The down-current slope is termed the lee-side and is formed by deposition of material moving from an up-current direction. Bucher (1919) termed the ratio between the chord and height as the vertical form index.

FIGURE 18

BEDFORMS IN PROFILE

After Allen (1968a)



The morphology perpendicular to water flow can be described in terms of the trace of the crestline and has been reduced to five basic patterns (Allen, 1968a). (Figure 19)

1. A bedform is straight if the crestline is rectilinear.
2. A bedform is sinuous when the crestline exhibits more or less smooth wave form.
3. A catenary bedform has a crestline trace with a pattern of a chain of catenary waves where the more pointed segments of the crestlines face down-current.
4. Linguoid bedforms have crestlines which open up-current.
5. Lunate bedforms have crestlines which open down-current.

Allen (1963) defines the span of a bedform as the dimension between the tips of the bedform measured at right angles to the direction of water flow and the horizontal form index as the ratio of the span to the chord.

An areally distinct assemblage of bedforms of much the same physical scale and shape is termed a train. Sinuous and catenary bedforms in train can be described as either in phase or out of phase. Linguoid bedforms found in phase are termed cuspate. (Allen, 1968b) If straight or catenary bedforms are strongly skewed relative to the general direction of water flow they are described as swept (Figure 20).

Most classifications of bedforms are based on the vertical form index or more commonly the spacing (chord). The current

FIGURE 19

BEDFORMS IN PLAN

After Allen (1968a)

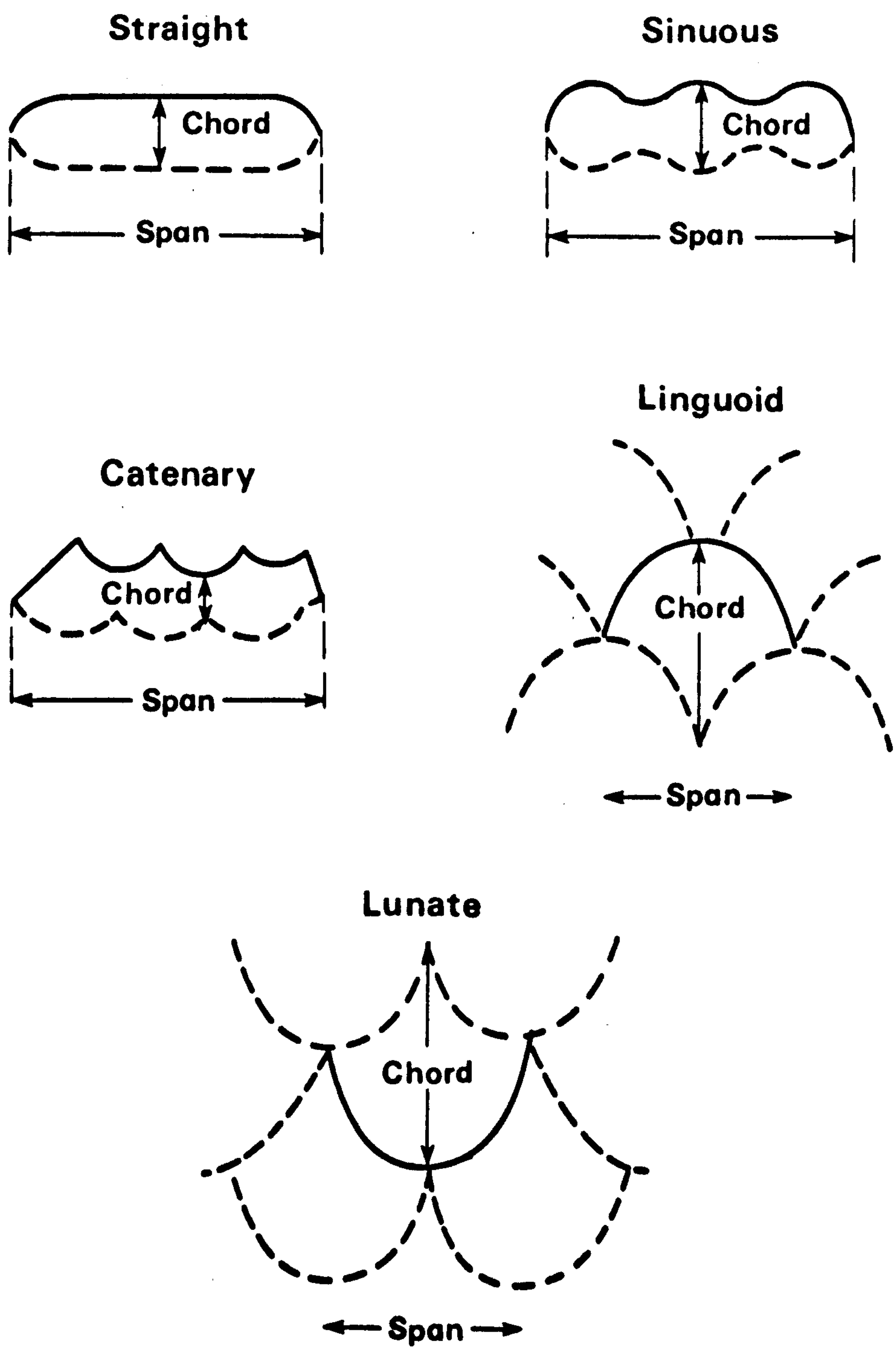
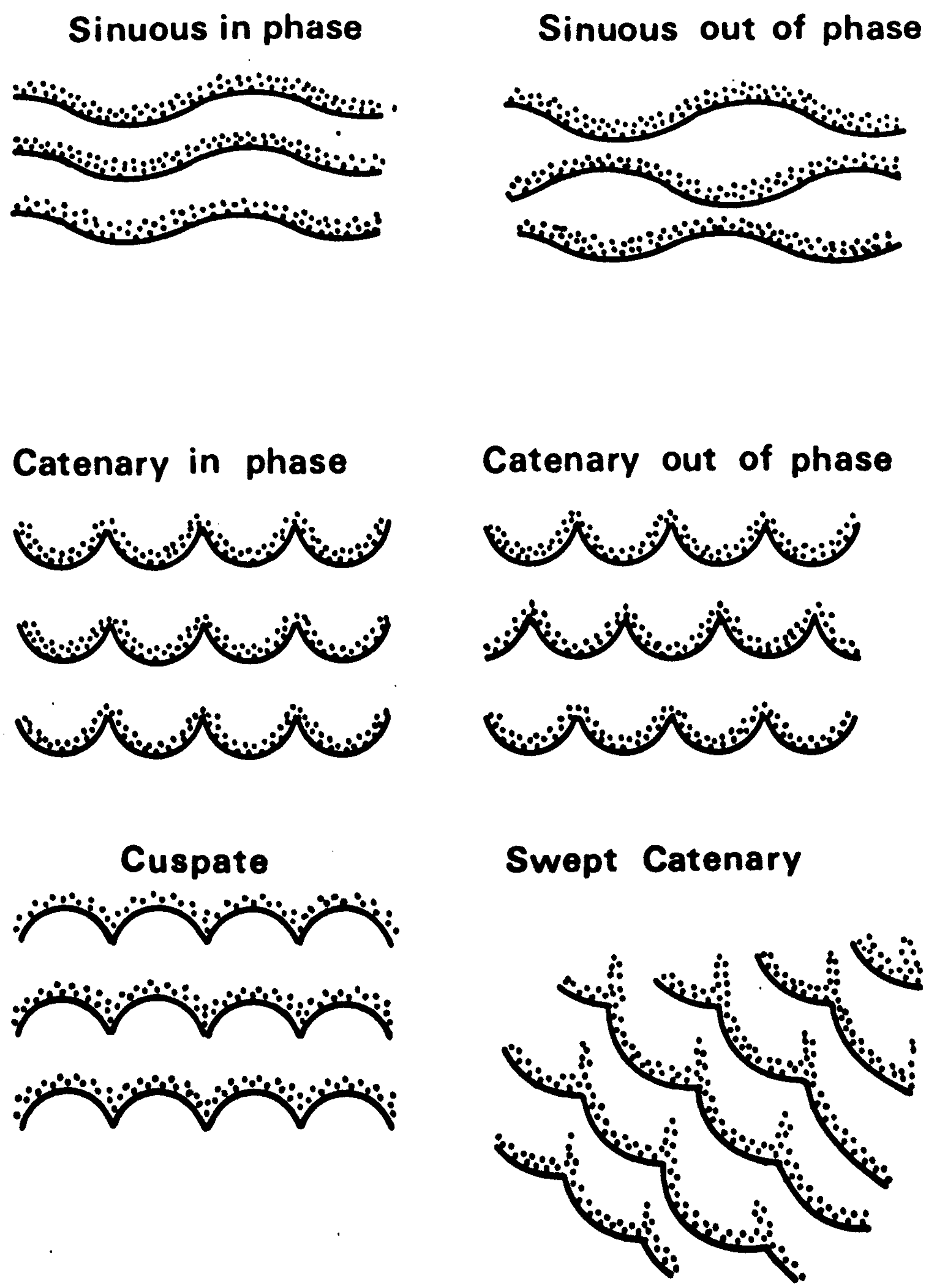


FIGURE 20

BEDFORM TRAINS

After Allen (1968a)



Lee-sides are stippled

confused state of bedform classification in the literature is due largely to differences in terminology. Also, several classifications were evolved from the study of bedforms in fluvial channels where several of the larger bedforms found in the estuarine environment do not occur.

Terms applied to bedforms include ripples, large-scale ripples, megaripples and sandwaves. Klein (1970), in a study of sandbanks in the Bay of Fundy, groups megaripples and sandwaves together as dunes and has a seperate category for large sandwaves. Allen (1968b) makes no distinction between megaripples and sandwaves classifying both as a large-scale ripples. Allen (1972) and the U.S. Naval Oceanographic Office (1966) define megaripples and sandwaves as the same bedform. The Hydraulics Division, American Society of Civil Engineers (1966) do not include megaripples in their classification.

Boothroyd and Hubbard (1974), in a study of the Parker and Essex estuaries of Massachusetts, classified bedforms on the basis of the vertical form index. Bedforms were measured on a 50-by 50-meter grid system and plotted as a graph of chords against heights. Several clusters of data points emerged and were used as a basis of classification. Ripples were classified as having chords less than 60cm. Megaripples have chords ranging from 60cm. to 6m. and sandwaves have chords greater than 6m. The chords of sandwaves had a wide spread but concentrated between 11 and 16m. Since sandwaves and megaripples considered together showed no trends in the vertical form index, the two types of bedforms were considered to be distinct groups and not part of a continuum.

A further distinction between megaripples and sandwaves was made on the basis of the crestline trace or morphology. Megaripples were found to be characterised by sinuous or cuspate crests whereas sandwaves were either straight or, infrequently, sinuous. A similar distinction was made by Hayes (1969) based on a study of esturaries in New Hampshire. Boothroyd and Hubbard (1974) defined a further group of bedforms as transition. These bedforms had chords clustering around 6m. and resembled dwarfed sandwaves with straight crests.

The method of Boothroyd and Hubbard was applied to the bedforms on the sandbanks in the Skegness area. A sample area of a 50-by 50-meter grid system was laid out with a tape measure and intersections marked at 10m. intervals by stakes. The chords and heights of all bedforms enclosed in the grid were measured either by tape measure in the case of ripples and megaripples and dumpy level survey in the case of sandwaves. A total of six grids were deployed, a minimum of one on each sandbank. Surveys, involving three people, were completed during the exposure of the sandbank for one tidal cycle. The data collected were plotted as a graph of chord against height (Figure 21). Only selected data points are plotted on the graph for cartographic clarity.

This graph is comparable in nearly all aspects with the graph based on bedform measurement in the Parker and Essex estuaries. The arguments of Boothroyd and Hubbard regarding group distinction of bedforms in their study area were also noticed for the bedforms in the Wash. The classification shown in Table 1 is used in this thesis. An additional category of large sandwaves was introduced to describe bedforms distinctly larger than sandwaves and occurring

FIGURE 21

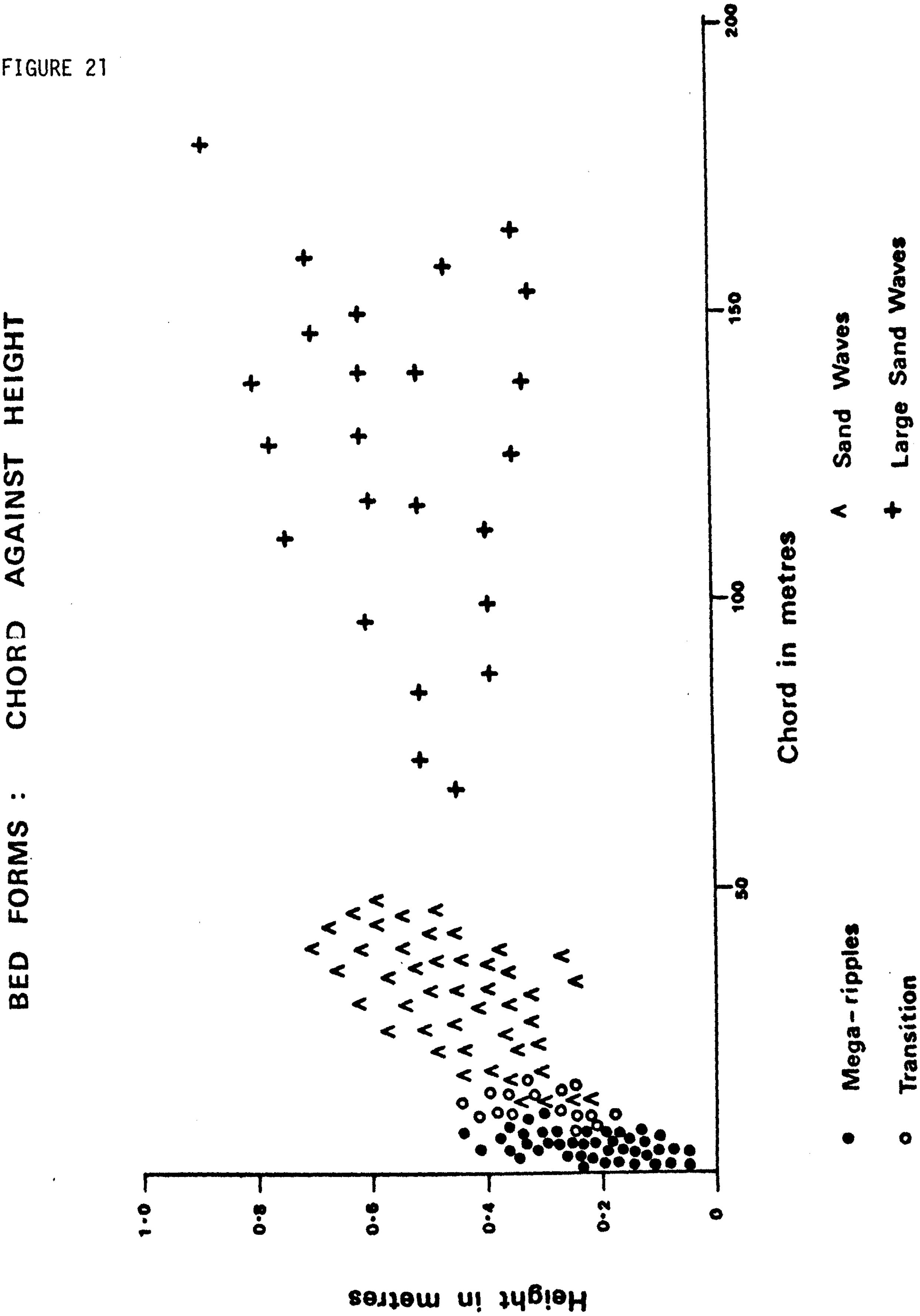

BED FORMS : CHORD AGAINST HEIGHT
Height in metres
1·0
0·8
0·6
0·4
0·2
0
50
100
150
200
Chord in metres
● Mega-ripples
○ Transition
^ Sand Waves
+ Large Sand Waves

TABLE 1

CLASSIFICATION OF BEDFORMS

	CHORD LENGTH	MORPHOLOGY
RIPPLES	Less than 6 cm.	Straight, sinous or catenary.
MEGARIPPLES	6 cm. to 6 m.	Sinuous, catenary, linguoid or cuspate.
SANDWAVES	Greater than 6 m. and less than 50m.	Straight or sinuous.
LARGE SANDWAVES	Greater than 50 m.	Straight.
TRANSITION	Cluster around 7 m.	Straight or sinous, resembling dwarfed sandwaves.

in areas distinct from those occupied by sandwave trains. Large sandwaves were commonly found to occur in association with megaripples, the latter being superimposed on the former. Their significance will be discussed later in this chapter.

BEDFORM SEQUENCE

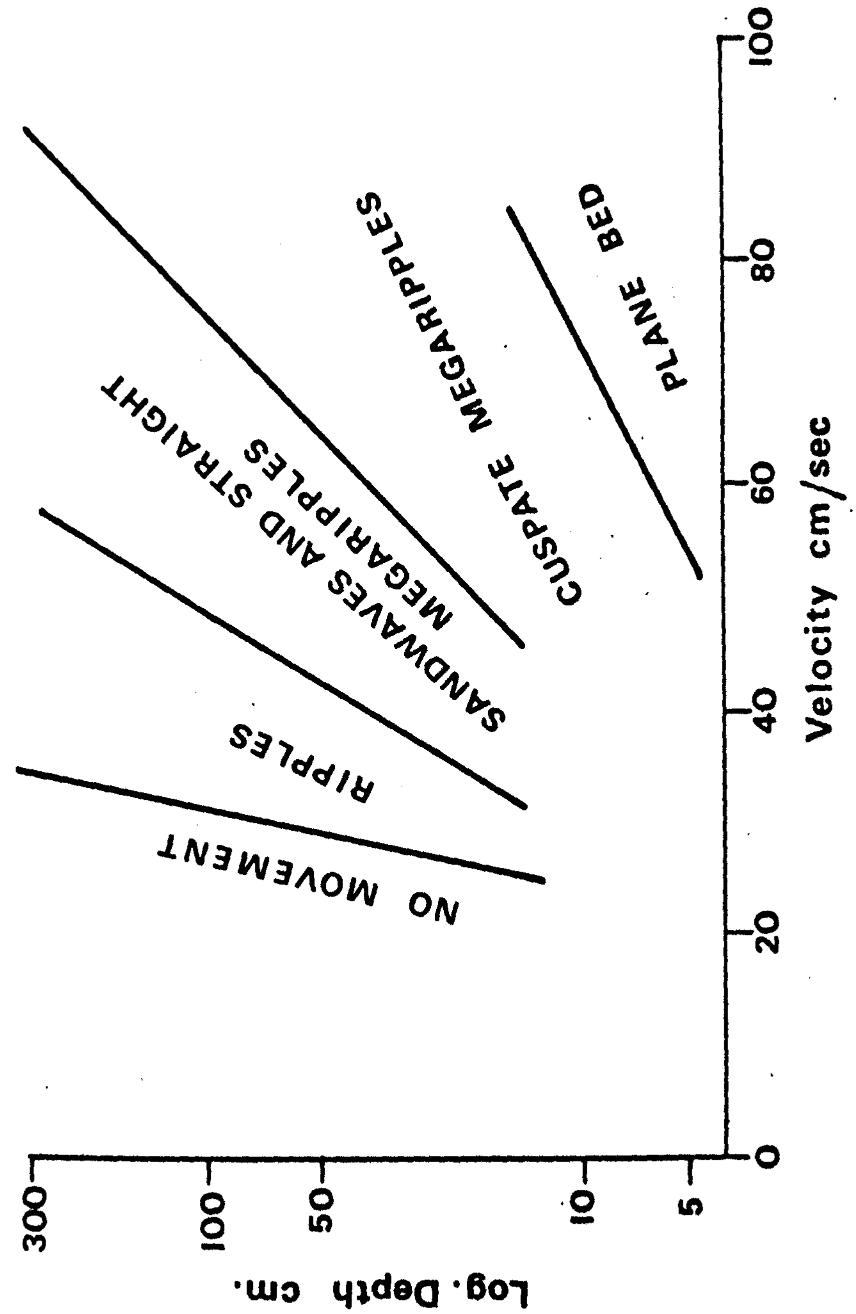
A sequence of bedform development related to the flow strength of water has been recognised in flumes (Simons, Richardson and Albertson, 1961; Simons, Richardson and Nordin, 1965; Williams, 1967), rivers (Sundborg, 1956; Brooks, 1958: Raudkivi, 1966) and estuarine environments (Boothroyd, 1969). The sequence, phrased in terms of the above classification, begins with straight ripples and goes to catenary ripples, termed low and high energy ripples by Harms, (1969). The sequence continues with straight megaripples and sandwaves, either straight or sinuous. Higher flow strengths result in cuspate, catenary, linguoid and sinuous megaripples. The sequence terminates in a plane bed, the result of a totally erosional environment.

Several studies have employed depth-velocity diagrams to delineate fields where each member of the sequence of bedforms occurs. Southard (1971) published diagrams based on the flume data of Guy, Simons and Richardson (1966). Boothroyd and Hubbard (1974) published a similar diagram for estuarine bedforms (reproduced as Figure 22) based on the delineation of field boundaries by diver observation of bedform changes under nonuniform flow conditions.

FIGURE 22

VELOCITY - DEPTH DIAGRAM FOR INTERTIDAL ESTUARINE BEDFORMS

(Reproduced from Boothroyd and Hubbard, 1974)



BEDFORM DISTRIBUTION

A map showing the areal distribution of bedforms, on the parts of the sandbanks exposed at low water, was constructed on the basis of aerial photographs and field survey. (Figure 23).

The Skegness Middle, Inner Knock, Outer Knock and Outer Dogs Head, tidal current ridges, are dominated by megaripple trains. The megaripples on the Skegness Middle are sinuous in plan and are superimposed at the northern and southern ends of the sandbank on large sandwaves. The megaripples on the Inner Knock vary in plan from sinuous at the southern end of the sandbank to cuspate at the northern extremity. (Figure 24). The north-eastern side of the sandbank exhibits several large sandwaves with superimposed megaripples. The Outer Knock displays a small train of large sandwaves on the eastern limb, devoid of a covering of megaripples. The megaripple trains on both limbs of this sandbank are sinuous at the northern ends but merge into areas of cuspate bedforms on the nose of the parabola. The Outer Dogs Head exhibits a train of sinuous megaripples.

The Inner Dogs Head, an ebb-tidal delta, exhibits a much more complex and varied association of bedforms. The western edge of the sandbank, both north and south of the flood shield, exhibits a very well developed sandwave train. The sandwaves at the southern end of the sandbank are straight but merge into sinuous bedforms immediately south of the flood shield (Figure 25). North of the flood shield the sandwaves are again straight with infrequent sinuous members. Immediately east of this sandwave train is a large area of megaripples, again superimposed on large sandwaves. The remaining area of the sandbank north of the flood

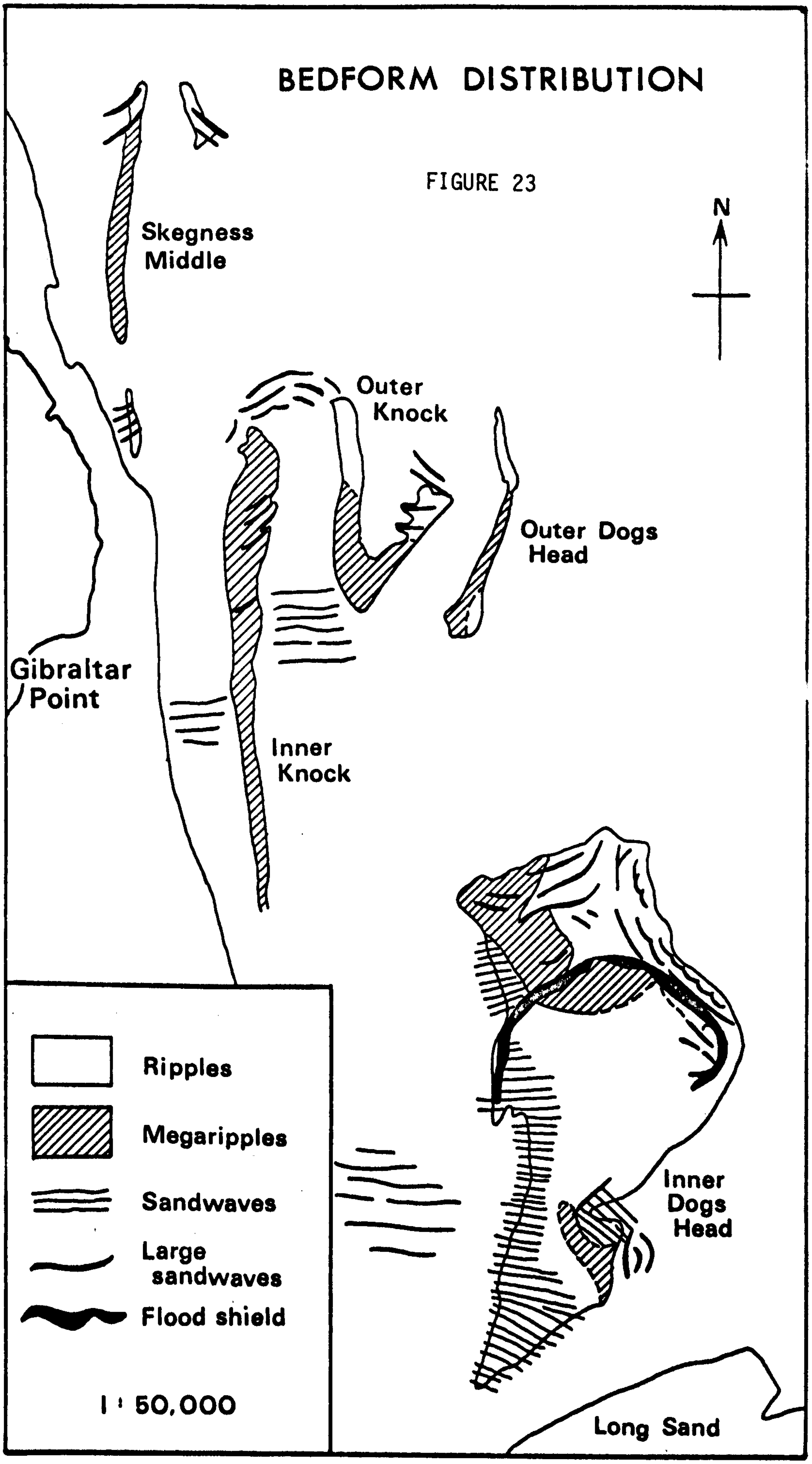

BEDFORM DISTRIBUTION
FIGURE 23
N
Skegness
Middle
Outer
Knock
Outer Dogs
Head
Gibraltar
Point
Inner
Knock
Inner
Dogs
Head
Long Sand
Ripples
Megaripples
Sandwaves
Large
sandwaves
Flood shield
1 : 50,000

FIGURE 24

CUSPATE MEGARIPPLES

FIGURE 25

SINUOUS SANDWAVES

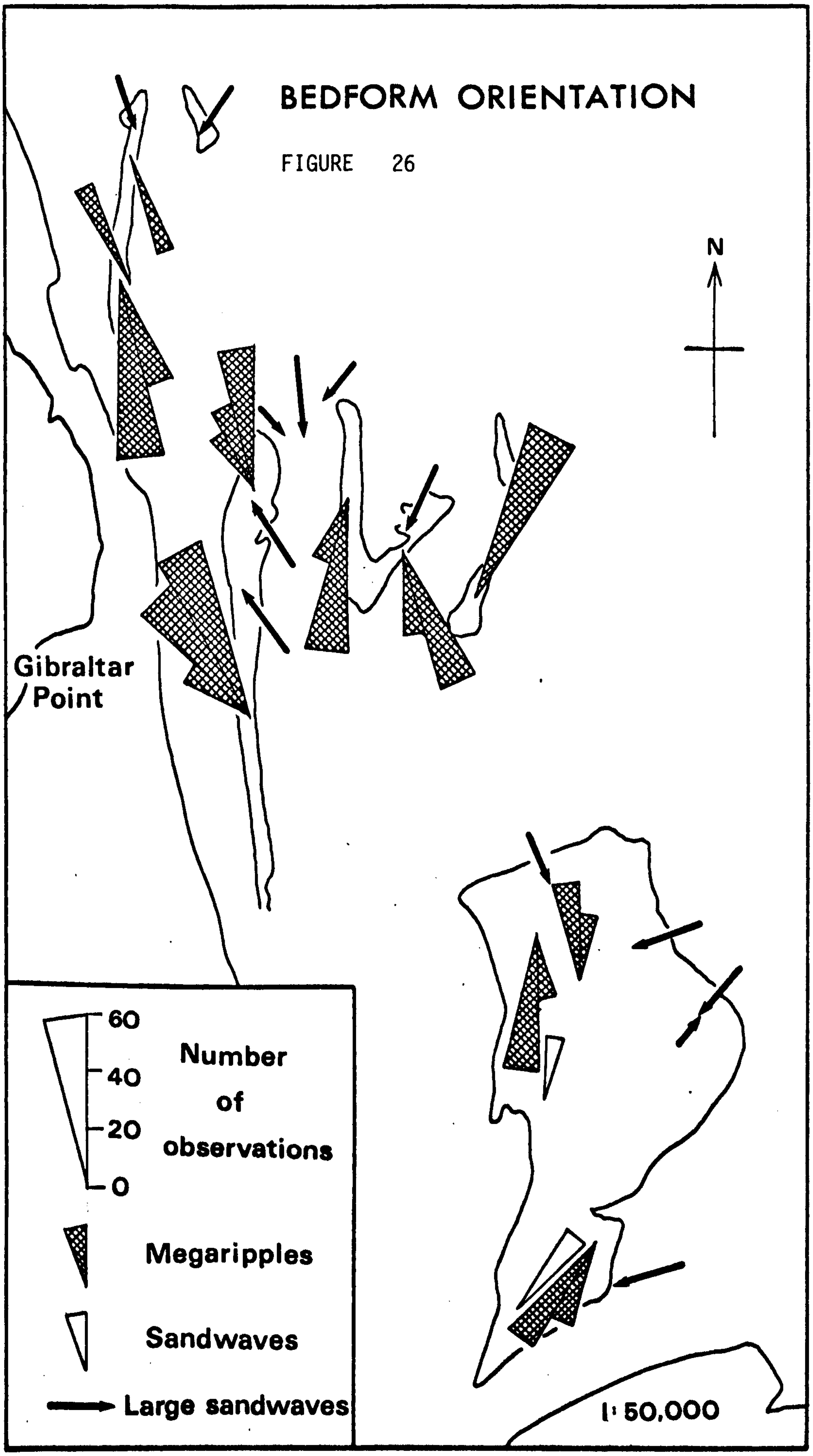
shield is dominated by large sandwaves with ripples superimposed on their surface. South of the central part of the flood shield, on ground sloping up to the crest of the shield, are trains of cuspate megaripples. The central part of the sandbank is an extremely flat area, drained by a small westward flowing river at low water, and covered by ripples. A complex area of bedforms is found west of the entrance to the Parlour Channel. A train of sinuous sandwaves merges into a train of cuspate megaripples in a south-westerly direction. Immediately seaward of the megaripple train is a small train of large sandwaves.

Echo-sounder profile runs were made along the long axes of the channels between the sandbanks to detect any bedforms present on the channel bottoms. The sensitivity of the instrument is such that only sandwaves, if present, could be recognised. Sandwave trains recognised in this way are shown on Figure 23.

ORIENTATION OF BEDFORMS

Since bedforms are maintained perpendicular to the direction of water flow and therefore, sediment movement, the orientation of the lee-side of a bedform indicates the local direction of sediment movement.

The orientation of the lee-sides of bedforms were measured on a 50-by 50-meter grid system. The grids were deployed in the manner described for bedform measurement and observations of lee-side orientations, for all bedforms in the grid, corrected for magnetic variation, were subdivided into 15 degree intervals and plotted as shown on Figure 26. The apices of the orientation


BEDFORM ORIENTATION
FIGURE 26
N
Gibraltar Point
60
40
20
0
Number of observations
Megaripples
Sandwaves
Large sandwaves
1:50,000

cones are at the location of the grid systems deployed for orientation measurement. Large sandwaves were measured individually and their orientations are shown by arrows on the map.

The megaripples on the tidal current ridges have orientations which are oblique to the long axes, and face the steeper sides, of the ridges. Observations of megaripple orientation at any one location had a spread of at least 30 degrees and in two cases a spread of 45 degrees. Observations of sandwave orientation, on the other hand, were confined to a 15 degree sector.

Since the sandwave trains in the Wainfleet Swatchway, the channel between the Inner and Outer Knocks and the Boston Deep are known only through echo-sounder profiles, no direct measurement of lee-side orientation can be made. However, from observation of the profiles it is clear that the sandwaves in the Wainfleet Swatchway face approximately south and the other two trains face north.

BEDFORM MIGRATION

Bedform migration rates in estuaries with reversing tidal flows have been monitored in several studies. Sternberg (1967) measured ripple migration in a tidal channel within Puget Sound, Washington. An average rate of migration of 1.0cm./5 minute period was recorded. Ludwick (1972) measured the migration rates of sandwaves in the entrance of Chesapeake Bay. The bedforms were measured 22 times over a 17 month period and movement rates of between 15 and 100m./ year, with an average of 63m./ year, were recorded. Boothroyd and Hubbard (1974) monitored megaripple and sandwave migration in the Essex and Parker estuaries, Massachusetts.

Megaripples were found to begin migration with an average speed of water flow of 60cm./sec. and reverse migration direction in sympathy with ebb and flood tides. Average megaripple migration rate was about 120cm./hour with significant migration during falling velocities and water depths at the end of a tidal cycle. Sandwave migration on a flood-tidal delta began at approximately the same water flow speed as megaripples. Migration during neap tides was 5 to 10 cm. per tidal cycle while migration during spring tides was 40 cm. per tidal cycle. Megaripple migration rates were found to be 10 to 50 times greater than sandwave migration.

An important observation (Sternberg, 1967), particularly in terms of the use of bedform migration rates in the development of a sediment movement model, is that sediment movement is approximately proportional to bedform migration rates. Bedform migration rate can, therefore, be used as an indication of the relative amounts of sediment movement in areas of differing bedforms.

However, the observation of Boothroyd and Hubbard (1974), regarding the ephemeral nature of megaripples, raises serious doubts about their use as indicators of sediment movement direction, particularly when observed at one state of the tide, in the case of this thesis, low water.

In the study area flood oriented megaripple trains are found on the Skegness Middle, Outer Knock and Inner Dogs Head which must have maintained their form during the flow of ebb tidal currents. It is important to note that the megaripples in these trains have planed off upper surfaces upon which are found ebb oriented ripples. Despite the fact that these megaripples have survived currents opposed to those responsible for their formation, it was thought necessary to establish at least a qualitative statement on the stability of megaripples in the study area. Since it was not possible in the present study to employ diver observation of bedform migration to establish the stability of megaripples under reversing tidal currents, an indirect indication of bedform migration direction was utilised, that of internal cross-stratification of bedforms.

Cross-strata are layers more or less steeply inclined to the principal surfaces of accumulation of the formation in which they are found. As early as 1908 Sorby, quoted in Allen (1968), perceived that the attitude of cross-strata indicated current direction. Allen (1968, p.97) states ".....the general connection between certain cross-stratification patterns and the migration of ripples is to be regarded as established.....". Since it is highly improbable that cross-stratification associated with a bedform will be completely removed by the deposition of a subsequent bedform, cross-stratification close to the surface of the sandbank should provide evidence of megaripples of opposed orientation if, in fact, they were ever present.

There are many methods described in the literature for the observation of cross-stratification. Initially the peel method of Yasso and Hartman (1972) was employed. A trench was dug into the sandbank surface, to the depth of the water-table (usually about 1 meter below the surface), parallel to the chord of the bedforms present. The trench was a minimum of 2m. in length. A smooth planar surface was then made on the sampling surface with a masons trowel. Spray adhesive, Type 77, marketed by the 3M Company, was then applied to the sampling surface and allowed to air cure for approximately 30 seconds. A backing board together with the adhered sand peel was gently removed from the sampling surface. This method proved only partially successful for application in areas where the sediment was wet. Cross-stratification could be recognised on several peels but the definition was considered poor.

An alternative method using a Senckenberg box sampler (Bouma, 1964) proved more successful. The box sampler was constructed of galvanised steel and consisted of two parts, an open ended base and a cover, with dimensions of 30 x 15 x 7.5 cm.

Prior to taking a sample the surface of the sand at the sample location was flattened and the base of the box was pushed into the sand until it was in firm contact with the sand surface. The top part of the box was then pushed over the base enclosing the sample on all sides but the bottom. The sand was dug away from the sides of the box and a steel plate was inserted across the open bottom. At this stage the orientation of the box was marked on the upper surface. The box was removed from the sand, holding the base plate, and laid down on the back side of the base and the cover removed and rotated 180 degrees and replaced on the base part. In this way the sample was completely enclosed by the metal box. The cover was then taped to the base and the box was transported to the laboratory in its original vertical position.

Samples were always taken so that the longest (30cm.) side of the box was vertical and the 15cm. side of the box was parallel to the chord of the bedform. Another box was then inserted directly below the position of the first sample and removed in a similar manner. In this way a sample of the upper 60cm. of the sand was removed for inspection.

On return to the laboratory the tape was removed, the box laid on its back and the cover removed, rotated 180 degrees and replaced, exposing only one surface, an originally vertical surface, of the sample. The sample was allowed to air dry.

When the sample was dry epoxy resin was poured carefully over the exposed surface, allowed to infiltrate the sand and cure. After two days the bonded surface sand grains were removed. The epoxy resin migrates through the sand at a rate depending on the permeability (related to grain size and packing) of the sand. Bands of coarse grained material, therefore, stand out in relief relative to finer grained bands and cross-stratification can be easily recognised. (Figure 26).

Five equally spaced sample sites, within the ebb oriented megaripple train, were chosen along the whole length of the Inner Knock. Of the five samples taken only one, from the northern extremity of the sandbank, contained evidence of cross-stratification opposed to the direction of the bedforms on the surface. Only 12% of the area of this sample contained flood oriented cross-strata, which rather surprisingly, appeared near the upper surface of the sample. This almost total lack of flood oriented cross-strata in the samples suggested that the megaripple trains in the study area are in fact relatively stable under opposing tidal current and could, therefore, be used as indicators of sediment movement direction.

Gellatly (1970) came to a similar conclusion regarding megaripples in King Sound, North Western Australia. Having studied the internal structure of megaripples he concluded that the external forms of megaripples, even in an area of alternating current directions, is a reliable indicator of facing of cross-strata and

FIGURE 27

RESIN PEEL

that this direction of facing reflects the mutually evasive paths of flood and ebb tides.

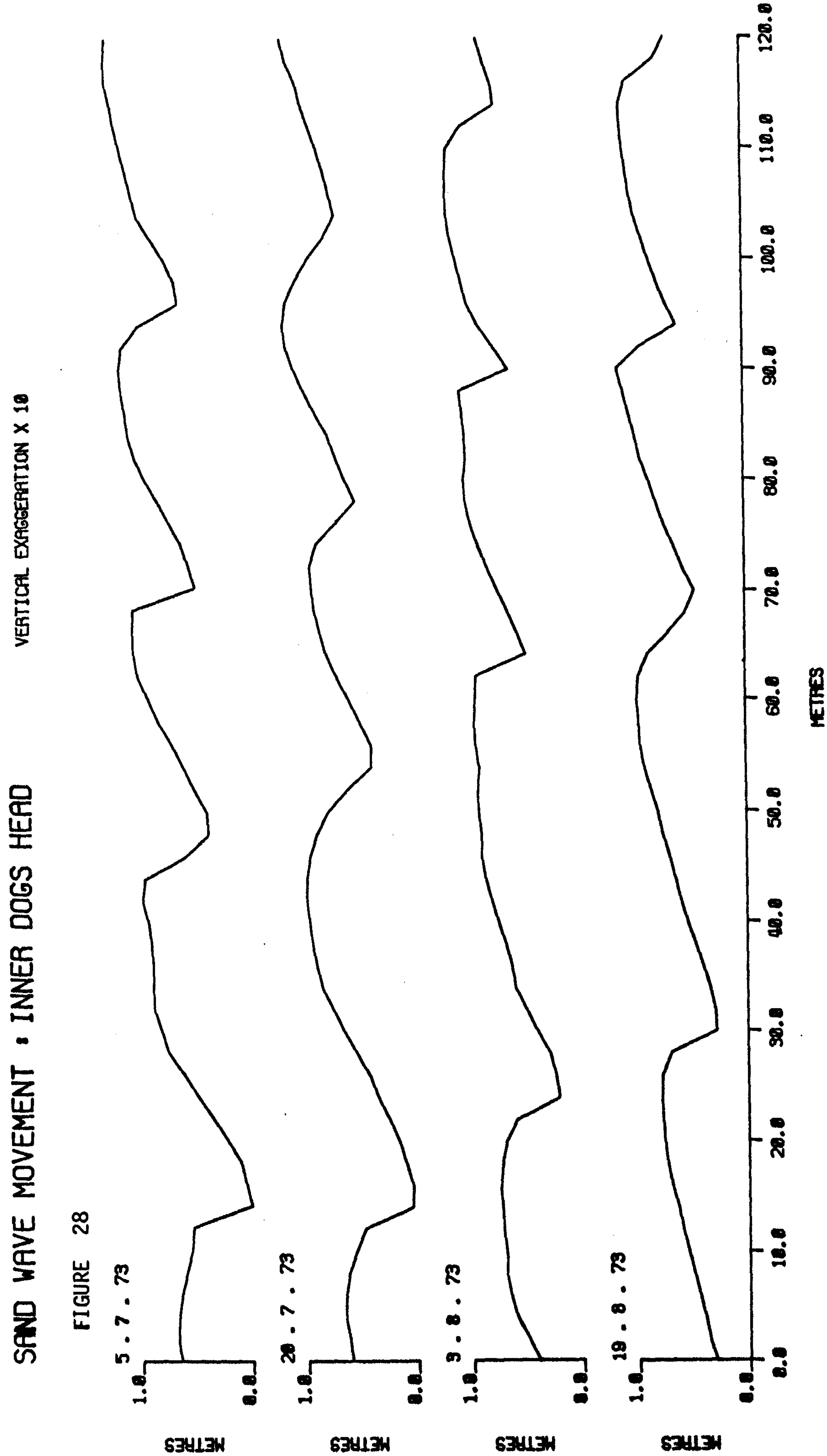
BEDFORM MIGRATION RATES IN THE STUDY AREA

It was hoped to be able to monitor migration rates of both megaripples and sandwaves by repeated survey at specific locations on the sandbanks. One important criterion for such an exercise is that individual bedforms must be recognisable from one survey to the next. In the case of megaripples this criterion could not be met, probably due to the high migration rates, associated with these bedforms, monitored by Boothroyd and Hubbard (1974) under direct observation. Sandwaves on the Inner Dogs Head, however, met the above criterion, sequences of bedforms being recognised by chord length of individual bedforms in the series.

A survey profile was established and marked at both ends by scaffold poles, of 2m. length, being hammered into the sand surface. The profile was intially surveyed on the 5th. August 1973 and repeated four times at approximately fortnightly intervals coinciding with spring tides (Figure 28). During this survey period individual bedforms maintained their chord lengths.

An average migration rate of 25m. in the 46 days of observation was recorded and represents an average migration rate of 27cm. per tidal cycle. This migration rate compares favourably with that measured by Boothroyd and Hubbard (1974) of 40cm. per tidal cycle on spring tides and 10cm. per tidal cycle on neap tides giving an average rate of approximately 25cm. per tidal cycle.

Since sandwave migration is of the same order in the study area and the Parker and Essex estuaries of Massachusetts and migration rates of megaripples in the latter area are 10 to 50 times



SAND WAVE MOVEMENT : INNER DOGS HEAD

FIGURE 28

greater than sandwave migration rates, these figures will be adopted during the following discussion on the information afforded by bedforms for a sediment movement model.

DISCUSSION

The following statements summarise the relationships between the various attributes of bedforms, discussed above, and sediment movement :-

1. The orientation of the lee-side of a bedform represents the local direction of sediment movement.
2. Bedforms occur in a hierarchical sequence related to the flow strength of water. Superimposition of bedforms higher in the sequence upon bedforms lower in the sequence reflects a change in the magnitudes of flow strength and sediment movement.
3. Migration rates of bedforms vary, higher migration rates indicating increased sediment movement.

Megaripple orientation, where measured on tidal current ridges, is oblique to the long axis of the sandbank. This divergence of megaripple orientation from the long axes of the tidal current ridges varies between 10 and 45 degrees. The megaripple train on the Inner Knock, with a long axis approximately north-south, varies in divergence from about 45 degrees at the midpoint of the sandbank to 15 degrees at the northern extremity. The megaripple train on the Outer Dogs Head diverges from the long axis of the sandbank by 15 degrees. On the western limb of the Outer Knock megaripple orientations diverge from the long axis by 15 degrees, those on the eastern limb by 30 degrees. On the Skegness Middle megaripple trains diverge from the long axis by 15 to 30 degrees. This ubiquitous divergence of orientation of megaripples from the long axes of tidal current ridges suggests that sediment movement is oblique across the sandbank.

The orientations of the lee-sides of bedforms in the study area show a strong bimodal pattern. The two groups of orientation are approximately north and south. The northerly oriented bedforms are those responding to ebb tidal currents and the southerly oriented bedforms are those responding to flood tidal currents.

The megaripple trains on the Inner Knock and Outer Dogs Head are oriented in a northerly direction suggesting a northerly movement of sediment from the Boston Deep and across these sandbanks. The northerly movement of sediment in the Boston Deep is confirmed by the northerly, ebb, oriented sandwaves on the floor of the channel. The flood oriented megaripple trains on the two limbs of the Outer Knock suggest a southerly movement of sediment in the channel enclosed by the limbs of the sandbank and across the sandbank itself.

The picture of megaripple orientation on the southern end of the western limb of the Skegness Middle is confused by the presence of two, opposed, megaripple trains. On the eastern side of the sandbank megaripples face north west in sympathy with ebb tidal currents whereas those on the western side face south-south east in sympathy with flood tidal currents. This arrangement of megaripple trains suggests movement of sediment towards the crest of the sandbank from adjoining parts of the Wainfleet Swatchway in an ebb direction and from the channel between the sandbank and the shoreline in a flood direction. At the northern end of the western limb of the Skegness Middle megaripple orientation is in a flood direction, suggesting a southerly movement of sediment. The large sandwaves on the western side of the southern end of the Skegness Middle face in a southerly direction and suggest a southerly movement of sediment in the channel between the sandbank and the shoreline.

The flood oriented sandwave train in the southern part of the Wainfleet Swatchway is evidence of a southerly movement of sediment in this part of the channel.

The distinction between large sandwaves and sandwaves is only one of size and large sandwaves probably have the same hydrodynamic relationship to water flow as sandwaves. Large sandwaves would, therefore, probably occur in the same position in the hierarchical sequence of bedform development as sandwaves. The large sandwaves on the Eastern side of the Inner Knock, the eastern limb of the Outer Knock and the Skegness Middle have linear and cuspate megaripples superimposed on their surface. This superimposition of bedforms represents flow strength intensities of different magnitudes at one location. The large sandwaves are probably relict forms when viewed at low water spring tides having developed during neap tides. They represent a smaller sediment flux during neap tide than during spring tide conditions.

The large sandwaves on the Inner Knock and the Skegness Middle face in the same direction as the superimposed megaripples suggesting the same direction of sediment movement during neap and spring tides. On the eastern limb of the Outer Knock the orientation of large sandwaves is almost parallel to the long axis of the sandbank whereas the megaripples diverge by 30 degrees. The difference in orientation could represent the deflection of water flow related to the strength of tidal currents.

The lee-sides of the large sandwaves on the nose of the parabola connecting the Inner Knock and Outer Knock face in a southerly direction in response to flood tidal currents. The plan shape of these bedforms is probably a reflection of the refraction of flood tidal currents as they approach the shallower water on the nose of the parabola. Sediment movement across these bedforms will be in a southerly direction.

The large sandwaves on the Inner Dogs Head north of the flood shield are all oriented in a southerly direction. The large sandwaves on the western side of the long axis of the sandbank face in a south-south easterly direction whereas those on the eastern side face in a south westerly direction. This orientation pattern is probably due to refraction of tidal currents similar to that described on the nose of the parabola connecting the Inner and Outer Knocks. Sediment movement across these large bedforms would be towards the central section of the flood shield, topographically the highest point, from either side of the long axis of the sandbank. The megaripple train on the north western corner of the Inner Dogs Head and the sandwave field immediately to the south west suggest southerly movement of sediment towards the flood shield.

The sandwave field which occupies the southern tip and the whole of the western edge of the sandbank south of the flood shield is ebb oriented representing a northerly movement of sediment. The megaripple trains immediately south of the flood shield are also ebb oriented and again represent a northerly movement of sediment towards the flood shield.

The central area of the Inner Dogs Head is flat and exhibits no large bedforms. The lack of large bedforms offers evidence of the effectiveness of the flood shield in protecting large areas of the ebb-tidal delta from modification by flood tidal currents. The only bedforms present are ripples with ebb orientations suggesting small amounts of sediment movement in a northerly direction.

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CHAPTER SIX

TIDAL CURRENTS

Five twelve hour tidal current stations were occupied at critical sites in the area of the sandbanks to deduce the nature of tidal current flow and predict movement of sediment on the sea-bed.

INSTRUMENTATION.

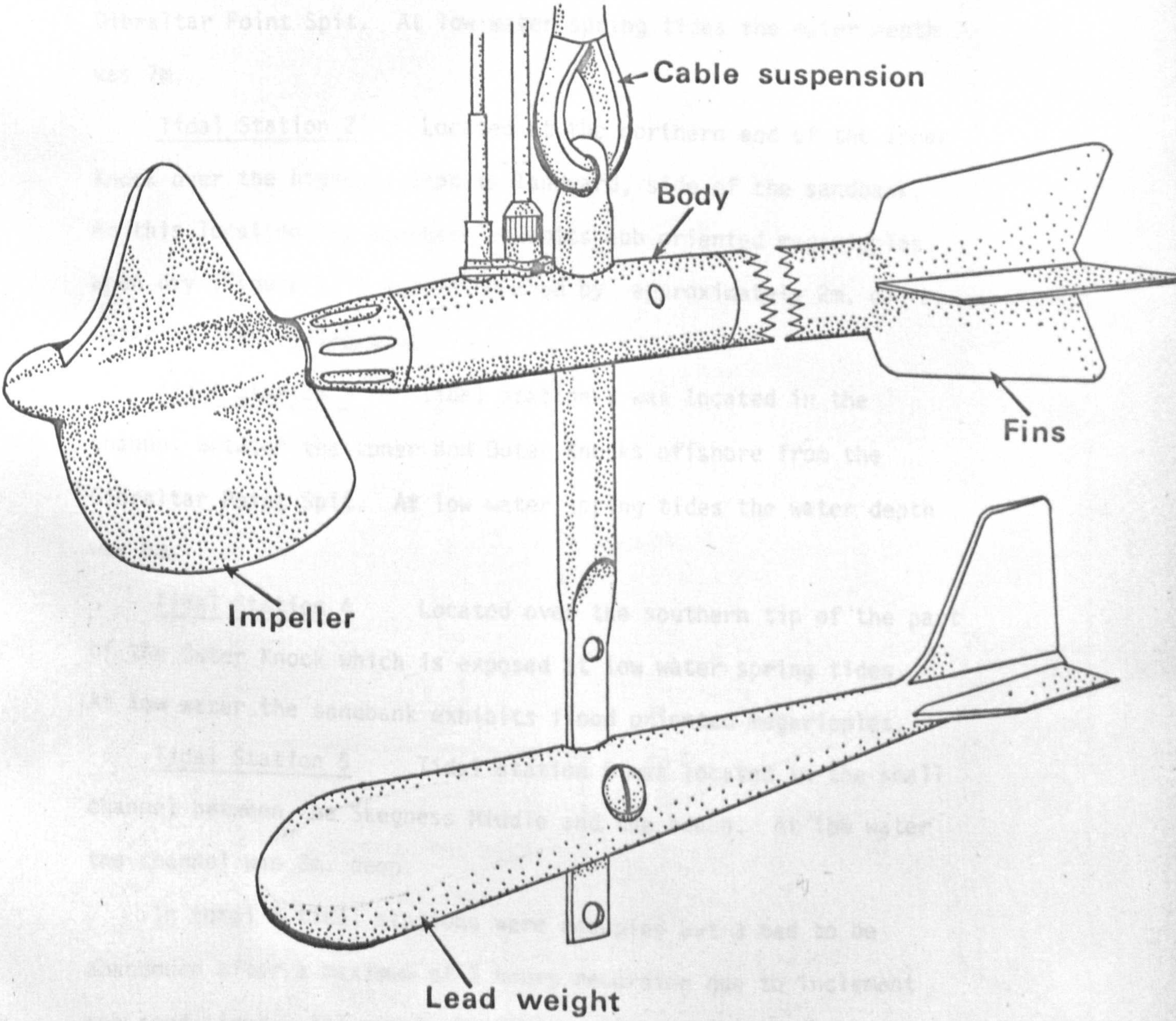
The instrument used in making field measurements was an Ott type 10.002 current meter. The instrument consists of a calibrated impeller attached to a barrel shaped body containing an impluse device triggered at each revolution of the impeller by a permanent magnet mounted on the sleeve if the impeller. The impeller has a diameter of 12.5cm., a pitch of 100cm. and is capable of measuring flow velocity of water to a maximum of 10m./sec. The body is connected to a tail piece with fins which orientate the instrument parallel to tidal flow. (Figure 29)

The instrument was suspended from a winch mounted to a counter-balanced derrick of which the arm and central post could be rotated relative to the boat, a 3.5m. fibre-glass dory, and locked in any position. The derrick arm was 3m. in length which allowed a minimum clearance of 2m. over the sides of the boat. The cable suspension system was kept vertical in the water by means of a 25kgm. lead weight attached 0.25m. below the current meter body.

The number of revolutions made by the impeller were recorded on a six-digit resetting counter with a maximum counting frequency of 10 impluses/sec. All measurements were made over a 50 second period by means of a built in control clock.

OTT CABLE MOUNTED CURRENT METER

FIGURE 29



LOCATIONS OF TIDAL CURRENT STATIONS

The locations chosen for tidal current stations are shown on Figure 30

Tidal Station 1 Tidal station 1 was located in the Wainfleet Swatchway between the Inner Knock and beach offshore from Gibraltar Point Spit. At low water spring tides the water depth was 7m.

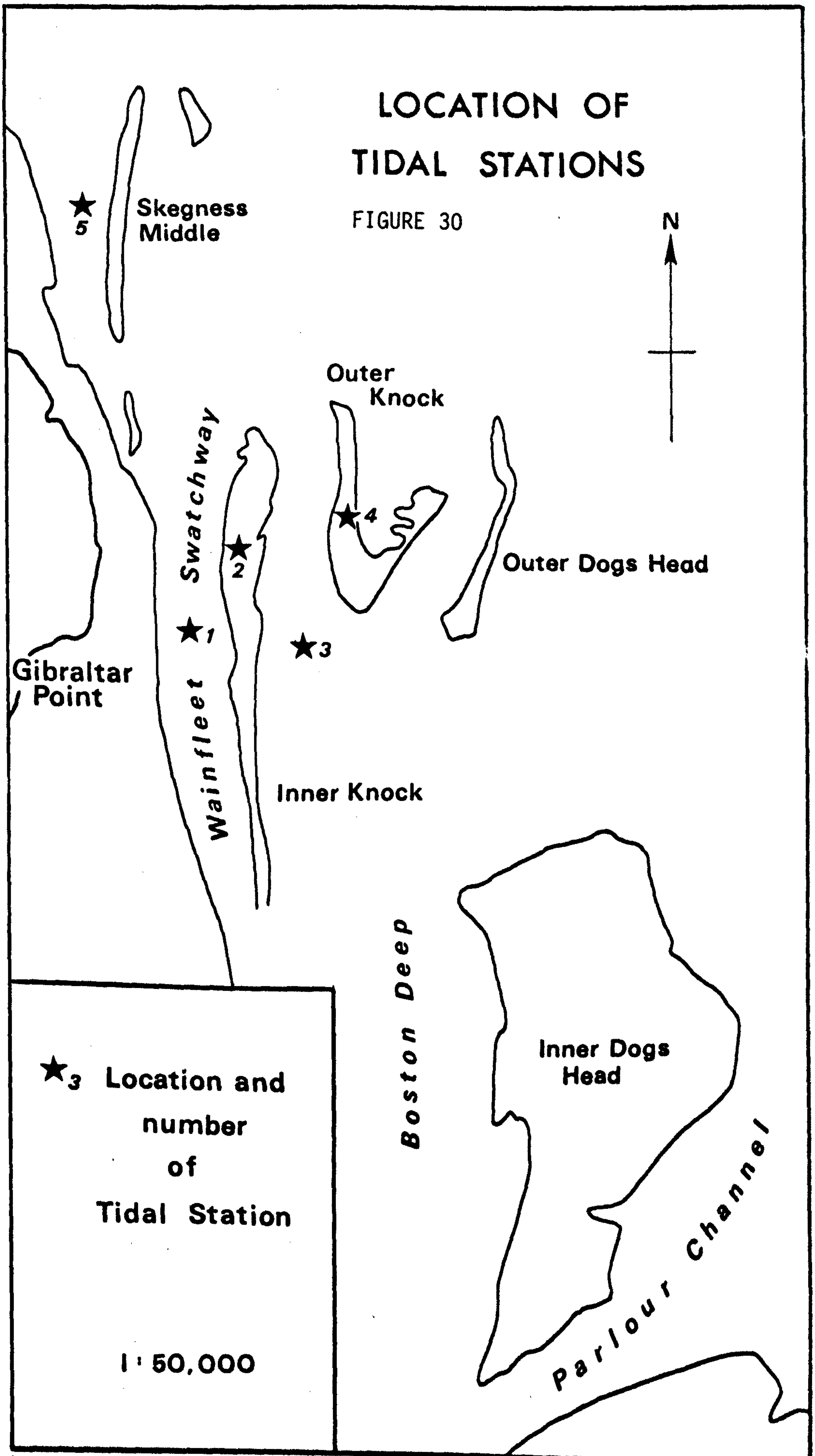
Tidal Station 2 Located at the northern end of the Inner Knock over the highest, that is landward, side of the sandbank. At this location the sandbank exhibits ebb oriented megaripples when dry (Figure 23) and is covered by approximately 2m. of water at high spring tide.

Tidal Station 3 Tidal station 3 was located in the channel between the Inner and Outer Knocks offshore from the Gibraltar Point Spit. At low water spring tides the water depth was 8m.

Tidal Station 4 Located over the southern tip of the part of the Outer Knock which is exposed at low water spring tides. At low water the sandbank exhibits flood oriented megaripples.

Tidal Station 5 Tidal station 5 was located in the small channel between the Skegness Middle and the beach. At low water the channel was 3m. deep.

In total 8 tidal stations were occupied but 3 had to be abandoned after a maximum of 3 hours recording due to inclement sea conditions. All tidal stations were occupied at times of spring tides.


LOCATION OF
TIDAL STATIONS
FIGURE 30
N
Skegness
Middle
5
Outer
Knock
Swatchway
4
2
Outer Dogs Head
1
3
Gibraltar
Point
Wainfleet
Inner Knock
Boston Deep
Inner Dogs
Head
Parlour Channel
3 Location and
number
of
Tidal Station
1 : 50,000

MEASUREMENT OF TIDAL CURRENTS

Arrival at tidal stations was timed at approximately one hour before the predicted time of high water and the stations were occupied for one complete twelve hour tidal cycle. The boat was anchored fore and aft to minimise movement due to changes in tidal current direction and compass bearings taken to a minimum of three identifiable landmarks to accurately assess boat location.

At each of the five tidal stations the following measurements were taken :-

1. The current meter was lowered to 0.6 of the depth from the surface to the seabed. Velocity of flow at this depth approximates the mean velocity of the water column (Gregory and Walling, 1973, p.127). The number of revolutions of the impeller in a period of 50 seconds was recorded every 15 minutes for the complete tidal cycle. The depth of the current meter was adjusted before each reading for changes in the level of the tidal plane. Measurements of this type would enable the assessment of net tidal residuals at each tidal station.

2. At approximately 1 hour intervals during the accelerating and decelerating part of the tidal cycle a velocity profile was measured at 0.5 m. intervals from 1 m. above the seabed to within 1 m. of the water surface. A 50 second measurement interval was again employed, the whole operation taking between 15 and 20 minutes depending on the depth of water at the tidal station. These velocity profiles would allow an assessment of the time of intiation of sediment movement and computation of sediment movement index.

3. The direction of movement of tidal currents at the surface was monitored at 15 minute intervals, coincident with the velocity measurements, using cork floats. The floats were released from the boat and their direction of movement recorded using a compass. Ideally tidal current direction should be assessed at the depth of measurement of velocity but no method of measurement was available at the time of the fieldwork.

4. A sediment sample was collected for each tidal station. The method of collection varied depending on the location of the site. At stations, 1, 3 and 5 located in tidal channels samples were collected using the grab described in Chapter 3 . At stations 2 and 4, located over sandbanks, samples were collected at low water when the bank was dry.

BOUNDARY SHEAR STRESS

Water flowing over a loose boundary, that is one on which sediment particles are available for transport, will exert forces which beyond an empirically derived threshold will move sediment particles. The forces operating on the particles give rise to shear stresses between the particles in motion and those forming the stationary boundary, with the fluid between the particles taking part in the shearing (Raudkivi,1967). This shearing force is known as boundary shear stress. Since boundary shear stress cannot be measured directly it must be determined indirectly from measurement of the velocity of water flow. Methods of determining boundary shear stress and thresholds of sediment movement will be evaluated.

DETERMINATION OF BOUNDARY SHEAR STRESS

There are several methods of estimating boundary shear stress. The most commonly used method employs the van Karman-Prandtl logarithmic velocity profile (Sundborg, 1956; Bowden, 1962; Smith, 1969) of the form :-

$$\frac{U}{U_\star} = 2.5 \ln\left(\frac{d}{Zo}\right) \qquad 1$$

where :- U = the flow velocity in cm./sec. at a distance d (in cm.) above the bed.

$U_\star$ = shear velocity in cm./sec.

Zo = roughness length in cm., which combines the effects of size, shape and distribution of bed roughness elements.

Having measured the velocity (U) at a minimum of three heights (d) near the bed, $U_\star$ and Zo are resolved using regression methods.

Boundary shear stress is evaluated using :-

$$\tau_o = U_\star^2 \rho \qquad 2$$

where :- τ_o = boundary shear stress in dynes./cm^2.

ρ = fluid density in gms./cm^3.

Hama (1954) demonstrates that the logarithmic distribution (equation 1) does not hold beyond 0.15D, where D is the boundary layer thickness, which can be taken as water depth for fully developed flow in uniform channels. The flow of tidal currents in the Skegness area can be assumed to be fully developed with an average depth flow of 2m. over the sandbanks and 10m. in the channels at highwater. The logarithmic distribution would, therefore, only be valid for the bottom 0.3m. of flow over the sandbanks and 1.5m. of flow in the channels.

Accurate measurement of the velocity of flow at different height intervals in the range from bottom to 1.5m. above bottom is not possible using a boat-mounted suspended current meter, the major problem being vertical boat movement with the passage of waves. In practise it proved impossible to measure current velocity within 1m. of the seabed.

Recently several studies of sediment transport have employed the quadratic shear stress law which related boundary shear stress to flow velocity and fluid density (Sternberg, 1968, 1970, 1972; McCave, 1971) :-

$$\tau_0 = C_D \bar{U}^2 \rho \qquad 3$$

where :- $\bar{U}$ = mean velocity in cm./sec.

C_D = dimensionless drag coefficient which relates the mean velocity near the seabed to the force exerted by the fluid per unit area of bed.

The value of this method is that the boundary shear stress can be evaluated using one measurement of velocity, $\bar{U}$ being defined as the mean current velocity at a standard height of 1m. above the seabed ($\bar{U}_{100}$) assuming a value of C_D is known for this height (C_{100}). The major problem of using this method is the choice of a value for C_{100}. Sternberg (1968) has shown that for hydrodynamically rough flows the drag coefficient assumes a constant value related to bed configuration and ranges between 2 x 10^{-3} and 4 x 10^{-3} for small bed roughness elements such as gravel and ripples. Large - scale ripples and sandwaves probably produce a drag coefficient that falls outside this range since they present a greater resistance to flow (Simons and Richardson, 1962). Ludwick (1974b) found that for an area of sandbanks in the entrance to Chesapeake Bay, with a moveable bed and size hierarchy of mobile bedforms including large scale ripples and sandwaves, C_{100} had a mean value of 1.3 x 10^{-2} but ranged through four orders of magnitude from 1 x 10^{-4} to 1 x 10^{0}. C_{100} was found to vary with $\bar{U}_{100}$ and $U_{\star}$ although the relationship was not consistent. Such large variations in the value of C_{100} suggests that this method is not suitable for estimating boundary shear stress in estuaries with strong tidal currents.

Measurements in flumes (Schlichting, 1968), for fully developed flow over flat surfaces, have shown that the distribution of velocity with depth, for the total depth of flow, can be represented by the velocity-defect law :-

$$\frac{U - u}{U_{\star}} = f\left(\frac{d}{D}\right) \qquad 4$$

where :- U = velocity of flow at the surface in cm./sec.

The velocity-defect law is based on an observed decrease of velocity with depth, but the relationship between the decrease invelocity and causative processes is not implied (Ludwick, 1974a).

Two empirically derived velocity-defect formulae are available, one of parabolic form (Hama, 1954) :-

$$\frac{U - u}{U_\star} = 9.6\left(1 - \frac{d}{D}\right)^2 \qquad 5$$

the other of logarithmic form (Dailey and Harleman, 1966) :-

$$\frac{U - u}{U_\star} = -8.6 \log \frac{d}{D} \qquad 6$$

Data from a velocity-depth profile at tidal station 1 (Table 2) will be used to illustrate the evaluation of all parameters relating sediment movement to tidal current flow.

Variables u, d and D in equations 5 and 6 are known from the velocity-depth profiles and the relationship between velocity (u) and the depth functions, empirically $9.6(1-d/D)^2$ and $-8.6\log(d/D)$ can be determined using least-squares linear regression (Davis, 1973). For the purpose of this analysis velocity (u) is the dependent variable and the depth functions (f(d/D)) the independent variables, the regression line being of the form :-

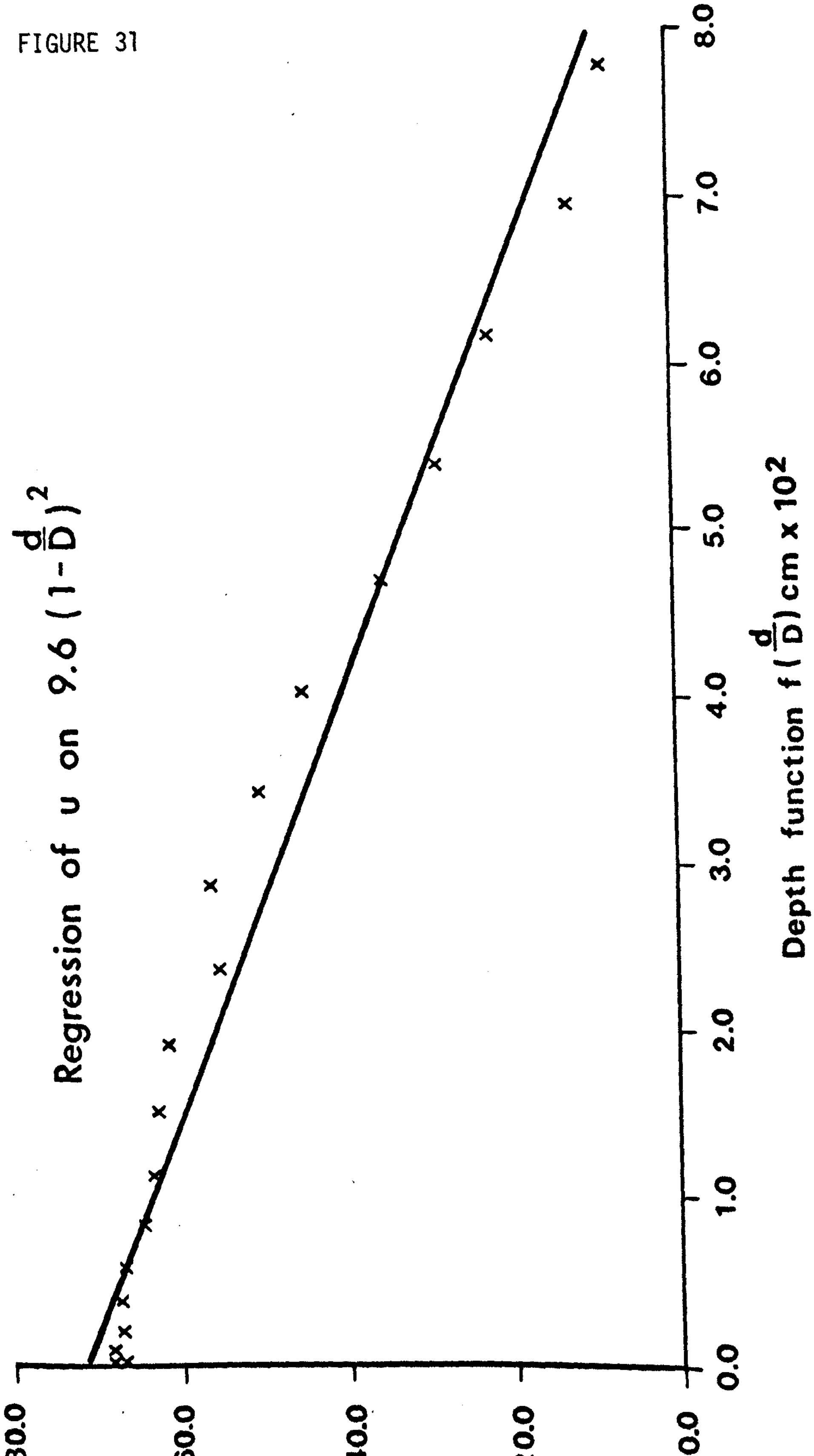
$$u = b_0 + b_1 f \frac{d}{D} \qquad 7$$

Figures 31 and 32 show regression analyses with the best fit lines and the original data points plotted, for the parabolic and logarithmic depth functions respectively. In the case of the parabolic depth function the Multiple Correlation Coefficient (R) is 0.9830 and the Goodness of Fit (R^2) is 0.9662. For the logarithmic depth function R is 0.9814 and R^2 is 0.9632. Both depth functions, therefore, show considerable agreement with the measured variation of velocity with depth. Analysis of 5 velocity-depth profiles demonstrates that the parabolic depth function had a consistently higher correspondance with the measured

TABLE 2

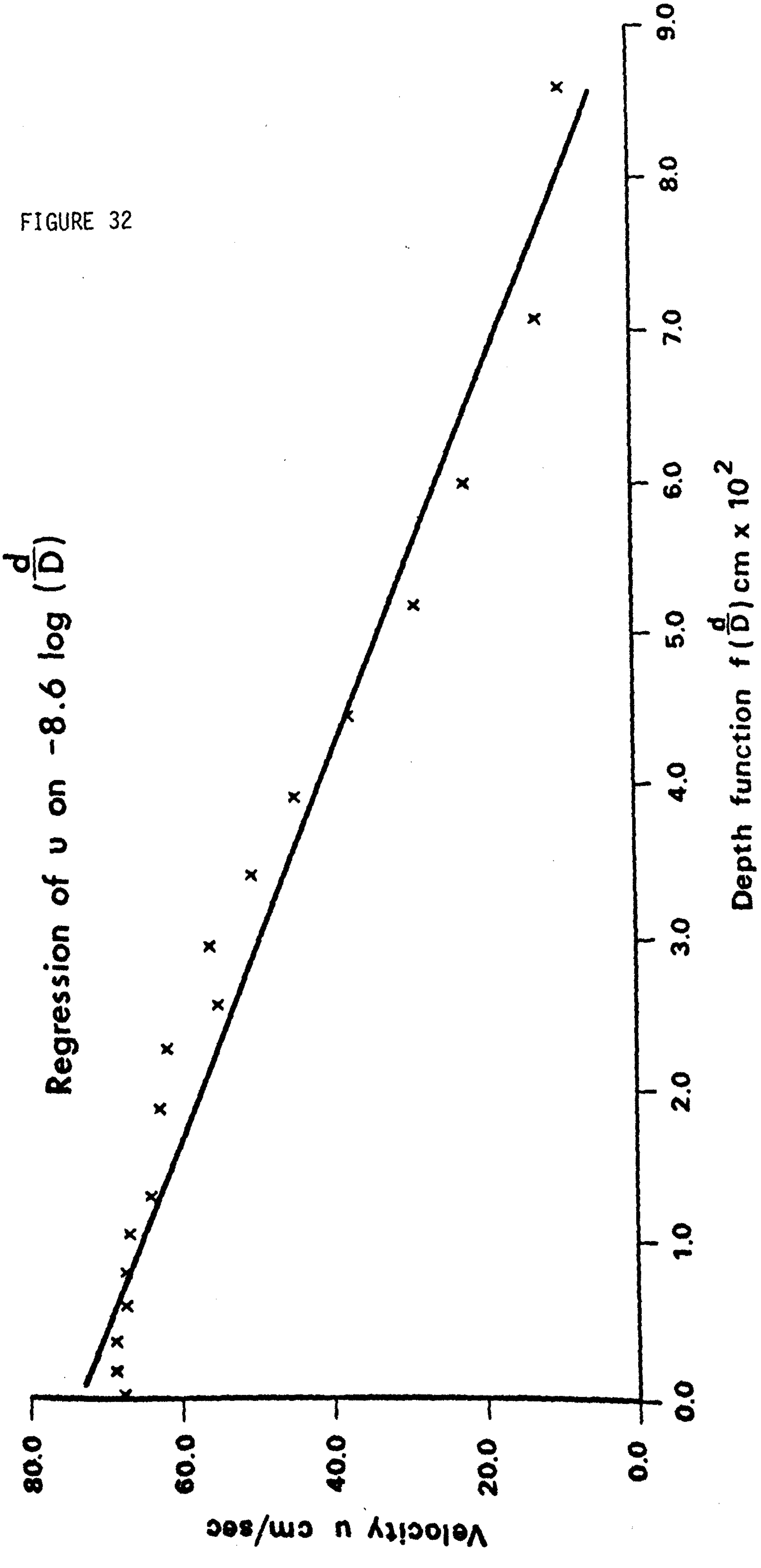
Distance from seabed (m)	Velocity (cm./sec.)
1.0	8.9
1.5	11.9
2.0	21.0
2.5	28.4
3.0	37.5
3.5	44.2
4.0	50.3
4.5	55.6
5.0	54.6
5.5	61.7
6.0	62.1
6.5	62.5
7.0	63.8
7.5	67.0
8.0	67.6
8.5	66.4
9.0	68.2
9.5	68.1
10.0	67.2

FIGURE 31



Regression of u on 9.6 (1 - d/D)²
Velocity cm / sec
80.0
60.0
40.0
20.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Depth function f (d/D) cm x 10²

FIGURE 32



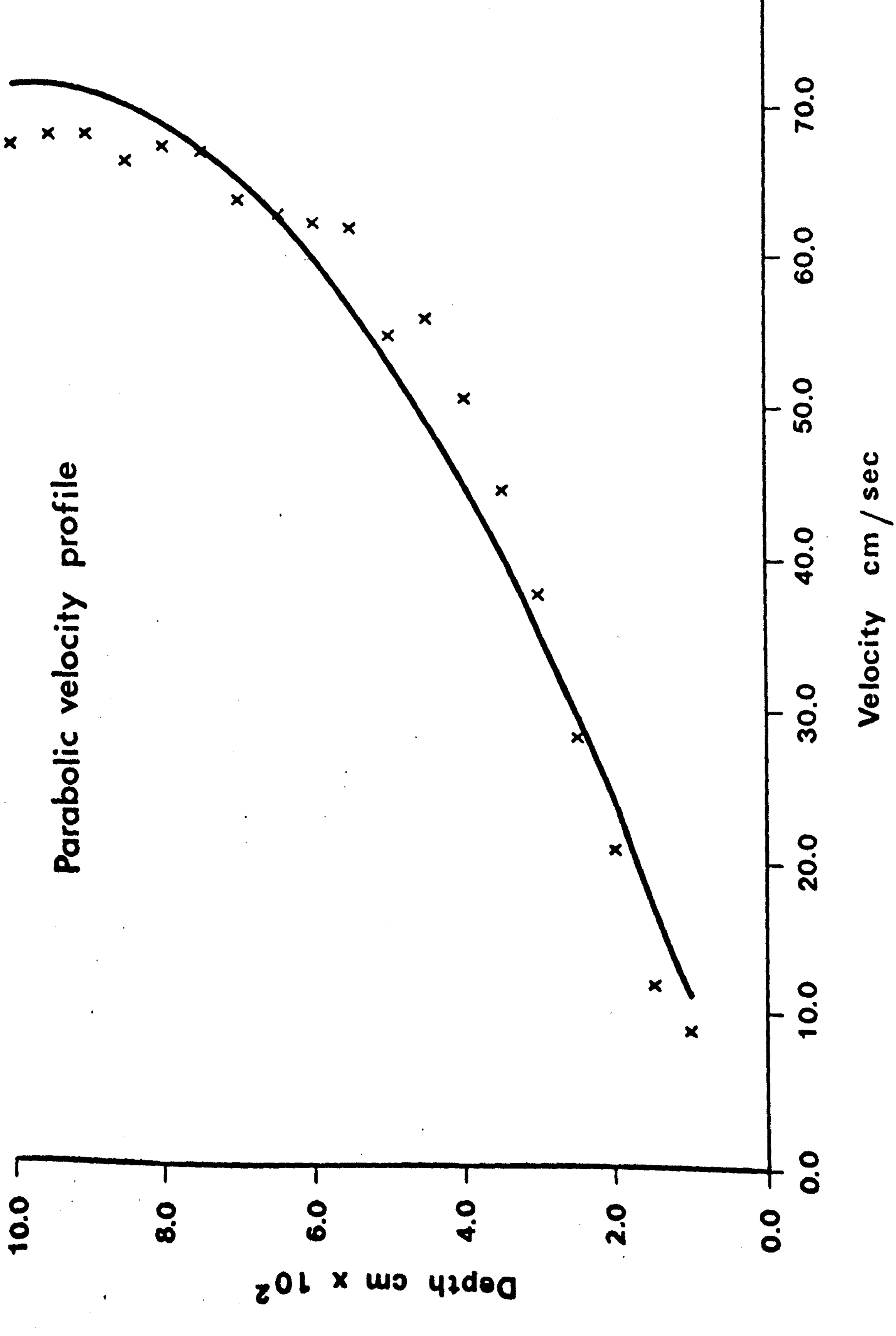
Regression of u on −8.6 log (d/D)
Velocity u cm/sec
80.0
60.0
40.0
20.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
Depth function f (d/D) cm x 10^2

velocity profile than the logarithmic depth function. Consequently the parabolic depth function was selected for subsequent analysis.

Figure33 shows the parabolic velocity profile plotted with the velocity-depth profile for the same data as used in the above analysis. Departures from the parabolic model present on this curve are characteristic of all profiles measured in the Skegness area. In a depth zone 3 to 6m. above bottom the departures are greater, and within the top 2m. of flow the values are less than those predicted by the parabolic model. Such departures are probably characteristics inherited from the laboratory derivation of this model and are indicative of the limitations of use in the field.

Several factors could contribute to the departures from the model, particularly the presence of sandbanks and moveable bedforms in the area which together produce a nonuniform boundary. Also flow may be unsteady, particularly at low velocities, although the fully developed state will be achieved during the accelerating periods of tidal flow. Vertical density gradients may be present in the water column although in the Wash, where there is a very small freshwater flux, such effects should be at a minimum. Finally, flows may be three-dimensional with secondarly directions of movement which were not present in the two dimensional laboratory experiments. None of these unsatisfactory features of the model are considered sufficient to negate its usefulness in the field, particularly when compared with the limitations expressed by Ludwick (1974a), in other methods of evaluation of boundary shear stress.

FIGURE 33



Parabolic velocity profile
Velocity cm / sec
Depth cm x 10²
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
2.0
4.0
6.0
8.0
10.0

Boundary shear stress is calculated from the regression equation (7). For the velocity-depth profile under consideration (Fig.34) the equation is of the form ;-

$$u = 0.7176 - 0.779\, f\left(\frac{d}{D}\right) \qquad 8$$

Surface velocity (U) and the relationship between u and f(d/D) can be determined from the above formula (8) and, by substitution in equation 5 , u* can be calculated. In this case u* is 6.2cm./sec. Substituting u* in equation 2 , the boundary shear stress (τ_o) is 46.13 dynes/cm^2 , assuming a fluid density of 1.20 gm./cm^3 . (The average density of seawater at Skegness is 1.20 gm./cm^3 . and does not vary significantly with ebb and flood tidal currents).

THRESHOLD OF SEDIMENT MOVEMENT.

The threshold of sediment movement is usually defined in terms of a dimensionless threshold stress criterion (θ_c) :-

$$\theta_c = \frac{\tau_c}{(\rho_s - \rho) g\, Gd} \qquad 9$$

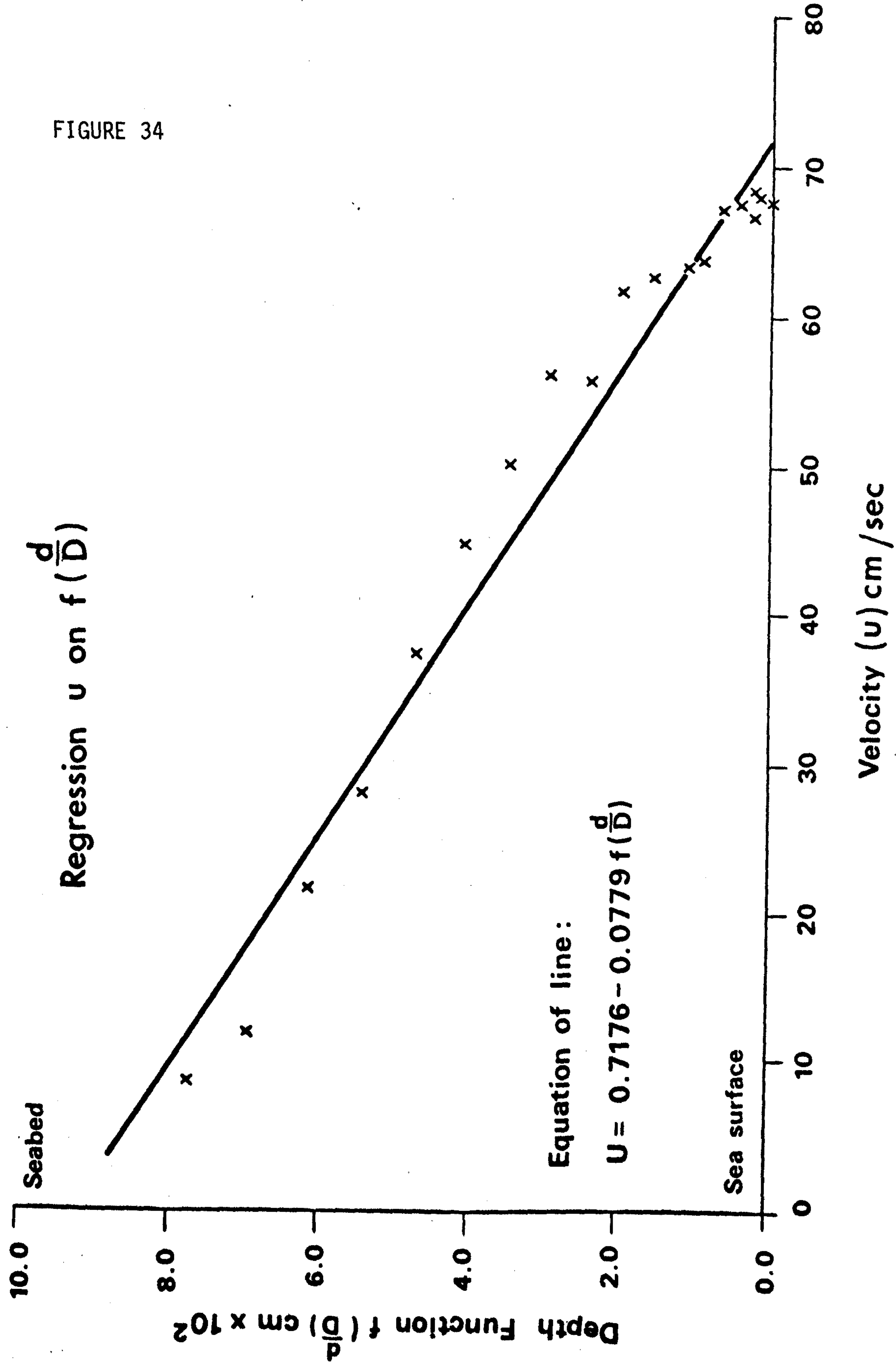
where :- τ_c = critical boundary shear stress in dynes/cm^2

g = acceleration due to gravity in cm./sec./sec.

Gd = grain diameter in cm..

Shields (1936) produced an empirically derived curve (Fig.35) showing the threshold of movement of quartz-density solids expressed in terms of grain diameter (Gd) and θ_c, the dimensionless

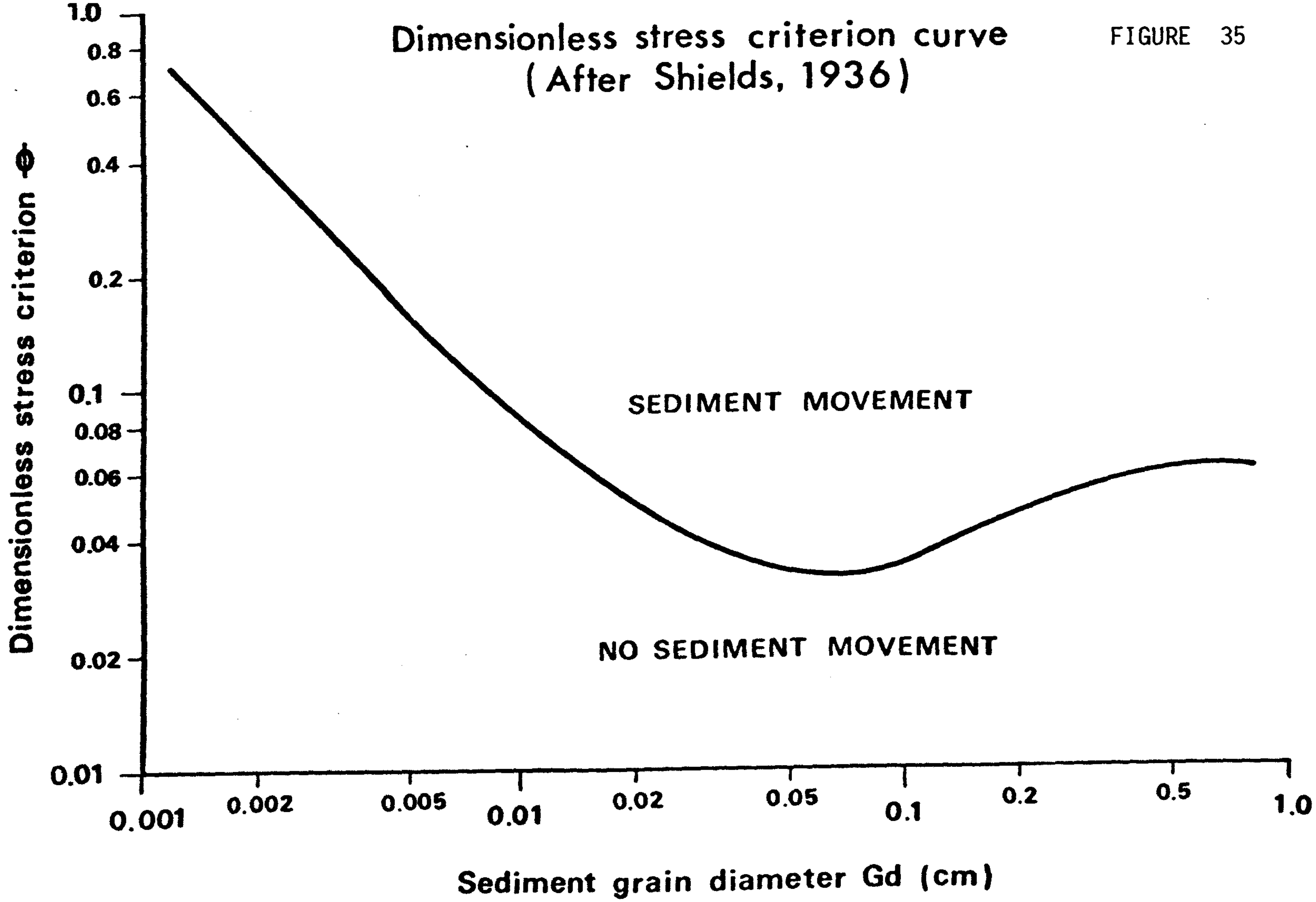
FIGURE 34



Regression u on f $(\frac{d}{D})$
Equation of line:
$U = 0.7176 - 0.0779\, f(\frac{d}{D})$
Seabed
Sea surface
Depth Function f $(\frac{d}{D})$ cm x 10^2
10.0
8.0
6.0
4.0
2.0
0.0
0
10
20
30
40
50
60
70
80
Velocity (u) cm/sec

FIGURE 35

Dimensionless stress criterion curve
(After Shields, 1936)



stress criterion.

From equation 9

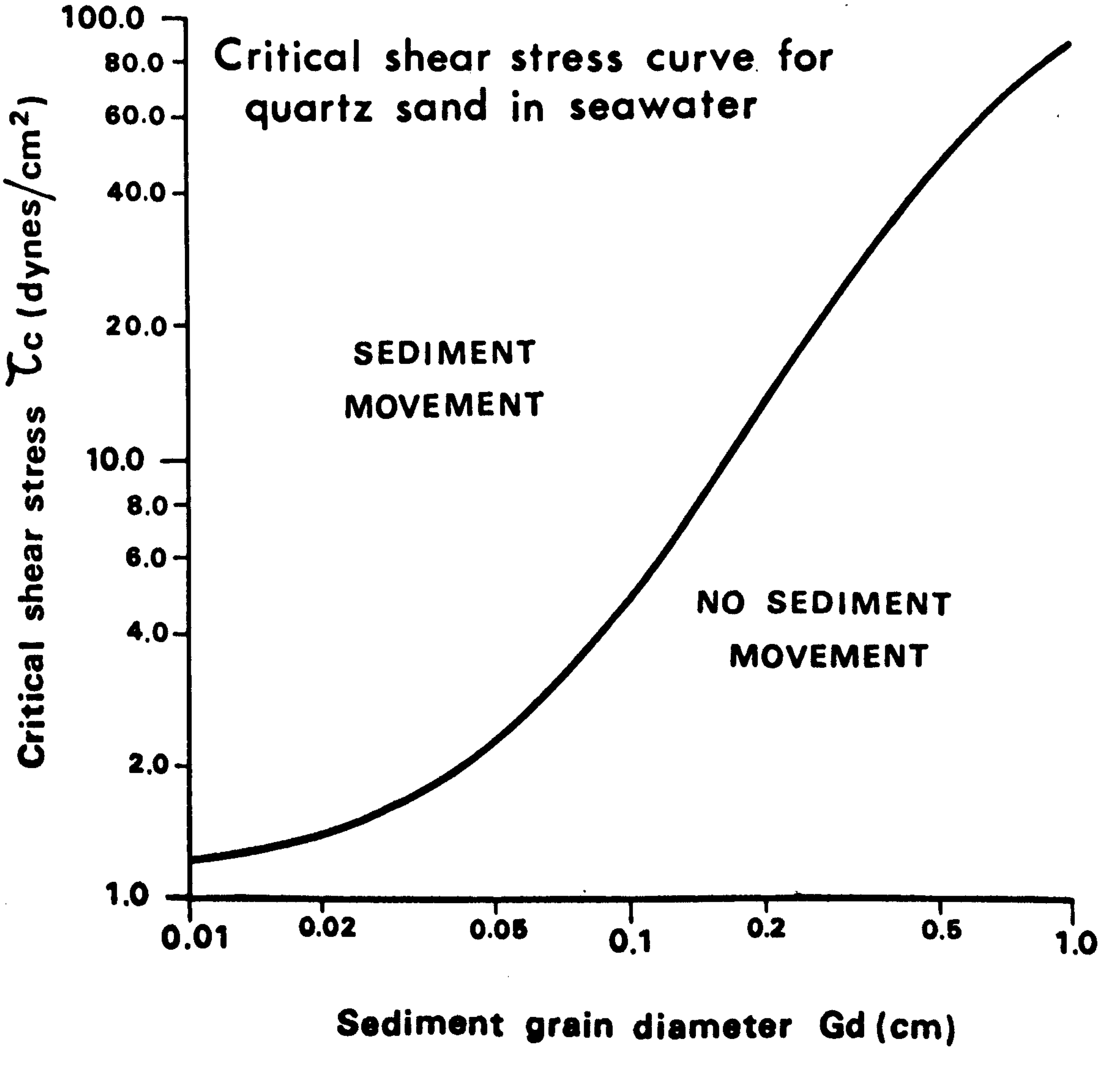
$$\tau_c = \theta_c(\rho_s - \rho)gGd \qquad 10$$

Values of the dimensionless threshold stress criterion (θ_c) can be estimated from Figure 35 for any grain size of sediment (Gd). Knowing the average density of sand grains (ρ_s) in the Skegness area to be 2.65 gm./cm^3 and the fluid density of seawater (ρ) to be 1.20 gm./cm^3 , values of the critical shear stress (τ_c) can be calculated from equation 10

A curve relating sediment size and critical shear stress for quartz sand in seawater can now be constructed from which values of τ_c can be determined for sand samples from the Skegness area (Figure 36).

The sand size fraction of the sediment sample from tidal station 1 had a mean size of 1.46 ϕ (0.04cm.) and the largest fraction retained in the sieves was -1.49 ϕ (0.28cm.). From figure 36 the critical shear stress (τ_c) for the mean grain size is 1.9 dynes/cm^2 and for the largest size fraction is 21.0 dynes/cm^2 Since the boundary shear stress (τ_o) for the velocity profile under consideration was 46.13 dynes/cm^2 all sediment of sand size would be in a state of motion.

FIGURE 36


Critical shear stress curve for quartz sand in seawater
SEDIMENT MOVEMENT
NO SEDIMENT MOVEMENT
Critical shear stress τ_c (dynes/cm^2)
100.0
80.0
60.0
40.0
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.01
0.02
0.05
0.1
0.2
0.5
1.0
Sediment grain diameter Gd (cm)

BEDLOAD TRANSPORT INDEX.

Techniques for the prediction of bedload transport rates have evolved from the work of Bagnold (1963), which related the mass transport of sediment as bedload to the power expended by the water moving over the sediment-water boundary. The relationship is expressed as :-

$$\frac{\rho_s - \rho}{\rho_s} gj = K\omega \qquad 11$$

where :- j = mass discharge of sediment in gm./cm./sec.

K = a proportionality coefficient

ω = a measure of power exerted on the bed by the fluid.

Problems in the use of this formula are related to the evaluation of the coefficients K and ω. Bagnold (1941) showed experimentally that K was a constant whose value depended on sediment size and sorting. Field data of Kachel and Sternberg (1971), from Puget Sound, Washington, suggested that K was not constant for any given flow but varied as a function of excess boundary shear stress, defined as $(\tau_o - \tau_c)/\tau_c$. This finding was supported by data from the flume experiments of Guy et.al. (1966). Sternberg (1972, p.76) gives a graph to estimate K if mean sediment diameter and excess shear stress are known. The fluid power (ω) was expressed by Bagnold (1963) as the product of boundary shear stress (τ_o) and mean fluid velocity ($\bar{u}$) near the boundary :-

$$\omega = \tau_o \bar{u} \qquad 12$$

Inman et.al. (1966) used the shear velocity (U_*) instead of mean velocity :-

$$\omega = U_*^3 \rho \qquad 13$$

Fluid power, therefore, is relatively easy to evaluate but determination of K depends on the use of Kachel and Sternbergs' data from Puget Sound which may not be representative of other tidal areas. A more realistic approach to the problem of bedload transport is to assume K is relatively constant (Bagnold, 1963), then from equation 11 :-

$$j \propto \omega \qquad 14$$

Following Ludwick (1974a) this assumption allows an estimate of a sediment movement index, where ω can be expressed as the product of boundary shear stress and velocity. $\bar{U}$ in equation 12 can be defined as the velocity at 1m. above the bed (U_{100}) :-

$$ji \propto \tau_0 U_{100} \qquad 15$$

where :- ji = bedload transport index

For the case study :-

ji = 46.13 x 11.12

= 512.96

MEASURED VALUES OF BOUNDARY SHEAR STRESS AND BEDLOAD TRANSPORT INDEX.

The times of measurement of depth-velocity profiles, relative to the tidal cycle, at tidal stations 1 to 5 are shown in Table 3 . At tidal stations 1, 3 and 5, located in channels, depth velocity profiles measured at each station were taken at the same times relative to the tidal cycle, 1½ hours, 2½ hours, 4 hours and 5 hours after high and low water. At tidal stations 2 and 4, located over the Inner Knock and Outer Knock respectively, the two velocity profiles on the ebb tide were measured at the same times as depth-velocity profiles 1 and 2 in the tidal channels. On the flood tide depth-velocity profiles at tidal station 2 were measured 3½ hours and 4½ hours after low water, the first being ½ hour after the submergence of the sandbank. At tidal station 4 depth-velocity profiles were measured at 2½ hours and 3½ hours after low water, the first again being ½ hour after submergence. These flood tide depth-velocity profiles departed from the sampling pattern in the channels to accommodate high velocities of water flow immediately after submergence, when the depth of flow is still small and sediment movement rates are likely to be high.

For each depth-velocity profile at each tidal station the boundary shear stress, velocity of water flow at 1 m. above the seabed and the bedload transport index were computed (Tables 4 to 8).

Analysis of the sand-sized fraction of the sediment samples for each tidal station produced values of mean and sorting shown in Table 9 .

The critical shear stress for the mean value for each sediment sample can be obtained from Figure 36 , and are shown in Table 10 .

TABLE 3

TIMES OF VELOCITY PROFILES AT TIDAL STATIONS

High — Low — High

0 1 2 3 4 5 6 7 8 9 10 11 12

Hours

Station number									
1	1	2	3	4		5	6	7	8
2	1	2	sand bank exposed			3	4		
3	1	2	3	4		5	6	7	8
4	1	2	sand bank exposed			3	4		
5	1	2	3	4		5	6	7	8

TABLE 4

TIDAL STATION 1.

Velocity Profile	Velocity at 0.6 depth cm/sec.	Boundary shear stress (τ_o) dynes/cm^2	U cm/sec.	Bedload transport index (ji)
1	49.5	36.32	10.27	372.89
2	40.3	32.48	8.14	264.3
3	32.1	25.31	5.76	145.86
4	18.3	8.36	3.89	32.6
5	9.2	2.1	3.0	6.32
6	63.2	46.13	11.12	512.92
7	57.3	39.62	10.76	426.4
8	21.4	17.3	3.88	67.2

$\bar{ji}$ (ebb) = 228.91

$\bar{ji}$ (flood) = 253.20

Residual ji 24.29 (flood)

TABLE 5

TIDAL STATION 2

Velocity Profile	Velocity at 0.6 depth cm/sec.	Boundary shear stress (τ_o) dynes/cm^2	U cm/sec.	Bedload transport index (ji)
1	53.6	44.2	15.21	672.3
2	61.2	51.6	17.3	892.8
3	35.7	24.2	12.34	298.62
4	22.6	20.1	8.7	174.87

$\bar{ji}$ (ebb) = 784.49

$\bar{ji}$ (flood) = 263.74

Residual ji 520.75 (ebb)

TABLE 6

TIDAL STATION 3

Velocity Profile	Velocity at 0.6 depth cm/sec.	Boundary shear stress (τ_o) dynes/cm^2	U cm/sec.	Bedload transport index (ji)
1	72.3	78.3	12.79	1002.1
2	75.6	84.21	12.54	1056.3
3	59.2	45.71	20.34	929.8
4	42.7	36.1	9.52	343.81
5	18.3	10.6	4.36	46.2
6	56.2	40.2	16.51	663.7
7	39.8	31.66	9.52	301.5
8	17.6	11.3	4.25	31.2

$\bar{ji}$ (ebb) = 833.00

$\bar{ji}$ (flood) = 260.65

Residual ji 572.35 (ebb)

TABLE 7

TIDAL STATION 4

Velocity Profile	Velocity at 0.6 depth cm/sec.	Boundary shear stress (τ_o) dynes/cm^2	U cm/sec.	Bedload transport index (ji)
1	57.3	46.16	12.32	568.69
2	56.2	39.1	12.55	490.7
3	67.1	59.2	19.21	1137.2
4	59.2	54.73	17.63	964.88

$\bar{ji}$ (ebb) = 529.69

$\bar{ji}$ (flood) = 1051.0

Residual ji 521.31 (flood)

TABLE 8

TIDAL STATION 5

Velocity Profile	Velocity at 0.6 depth cm/sec.	Boundary shear stress (τ_o) dynes/cm^2	U cm/sec.	Bedload transport index (ji)
1	51.3	43.65	11.43	498.72
2	39.2	31.5	9.05	285.1
3	30.1	21.43	7.9	169.3
4	17.8	9.2	5.85	53.8
5	39.6	36.81	10.46	385.2
6	62.3	50.23	11.97	601.3
7	48.7	42.15	12.45	524.6
8	12.2	8.3	5.86	48.62

$\bar{ji}$ (ebb) = 251.73

$\bar{ji}$ (flood) = 389.93

Residual ji 138.2 (flood)

TABLE 9

Tidal Station	Mean		Sorting (phi)
	Phi.	cm.	
1	1.463	0.037	0.485
2	-0.361	0.125	0.463
3	1.573	0.034	0.356
4	0.213	0.088	0.355
5	1.384	0.03	0.366

TABLE 10

Tidal Station	Critical shear stress (dynes/cm^2)
1	1.9
2	6.6
3	1.8
4	4.1
5	1.75

Since all values of sorting fall within the range 0.35 to 0.5 all sediment samples can be classified as well sorted (Chapter 3, this thesis), the critical shear stress for the mean value of sediment size will be taken as that necessary for the initiation of sediment movement at each tidal station. Values of critical shear stress can be compared with the boundary shear stress for each depth velocity profile to approximately evaluate the time of initiation of sediment movement and the duration of sediment movement at the tidal stations.

However, comparison of the values of critical shear stress for sediment at each tidal station with measured values of boundary shear stress shown in Tables 4 to 8, shows that at all tidal stations at the times of measurement of depth-velocity profiles sediment would be in motion. For example at tidal station 1 the critical shear stress for sediment at that location is 1.9 dynes/cm^2 and the lowest recorded boundary shear stress is 2.1 dynes/cm^2. It would appear, therefore, that sediment motion occurs at all states of the tide except a short period, at most 1½ hours, around high and low water. Tidal currents in the Skegness area are, therefore, competent to transport available sediment for a minimum of 75% of the time.

In terms of a sediment movement model the net direction of transport of sediment at each tidal station is a more important factor than the actual duration of competent water flow. Since the depth-velocity profiles were measured at the same time intervals during ebb and flood flow, in the tidal channels, the bed - load transport indices measured on the ebb tide can be compared with those measured on the flood tide. To assess net direction of sediment transport the average bedload transport index for the ebb and flood tides was computed for each tidal station. The difference between average ebb and flood transport indices represent a residual of sediment movement in either ebb or flood directions.

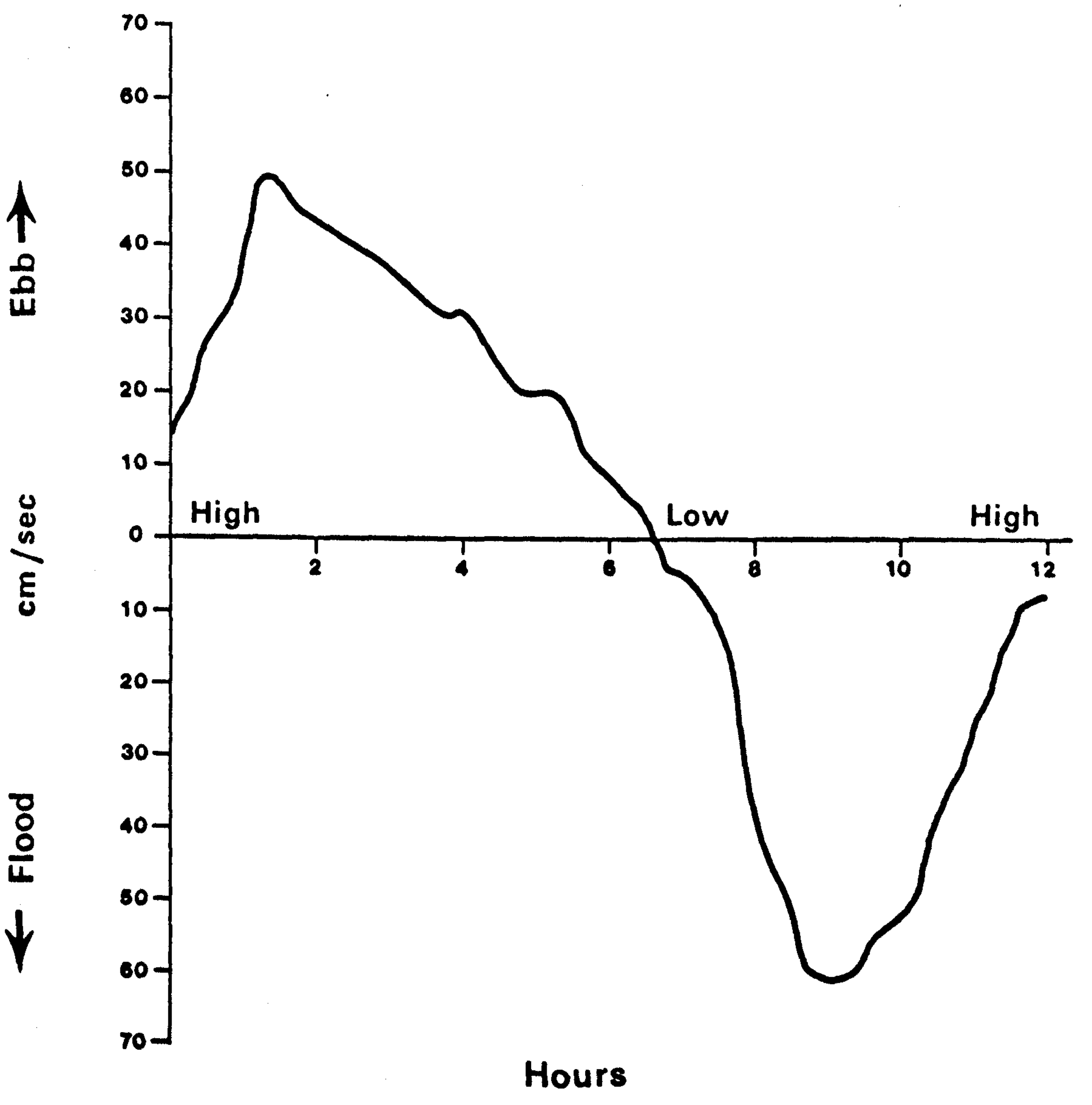
At tidal station 1 located in the Wainfleet Swatchway and tidal station 5 located in the channel between the Skegness Middle and the shoreline small flood residuals of bedload transport index were monitored of 24.29 and 138.2 respectively. At tidal station 3 located in the Boston Deep a large ebb residual of 572.35 was recorded. At tidal station 2 located over the Inner Knock, tidal station 4, the residual was in a flood direction with a value of 521.31.

TIDAL CURRENT VELOCITY CURVES

The curves of mean velocity of the water column over a full tidal cycle for tidal stations 1 to 5 are shown in Figures 37 to 41 respectively. At tidal stations 1, 3 and 5 located in channels a common feature of the tidal current velocity curves is the length of time occupied by the ebb tide compared with the flood tide. In all cases the ebb tide ran for a longer period of time than the flood tide, that is approximately 6½ hours compared with 5½ hours. Differences in the curves are manifested in the peak velocities achieved on either ebb or flood tides. At tidal station 1 located in the Wainfleet Swatchway the ebb tide had a peak velocity of 50 cm./sec. 1¼ hours after high water and the flood tide had a peak velocity of 59 cm./sec. 3 hours after low water.

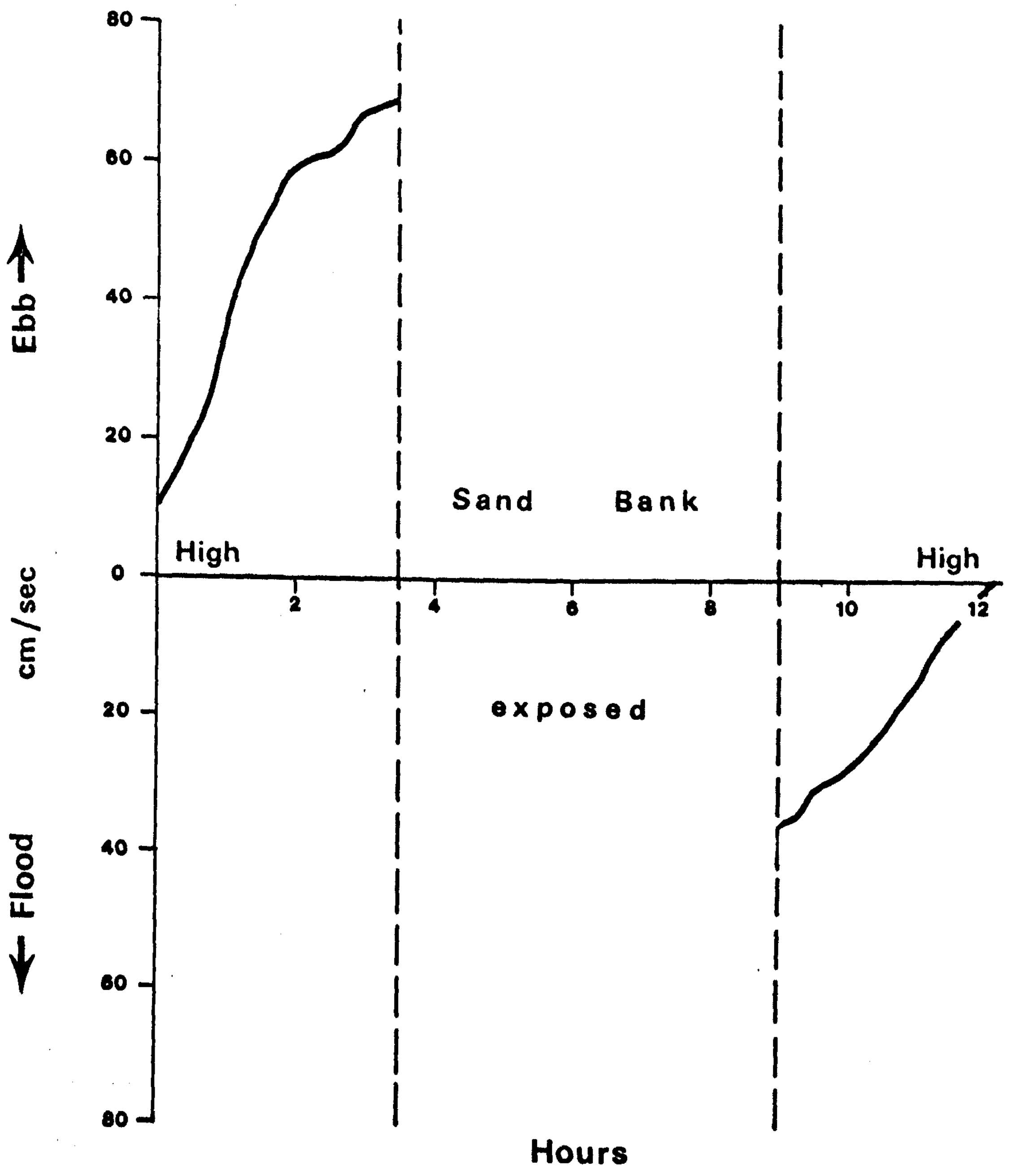
TIDAL STATION 1

FIGURE 37



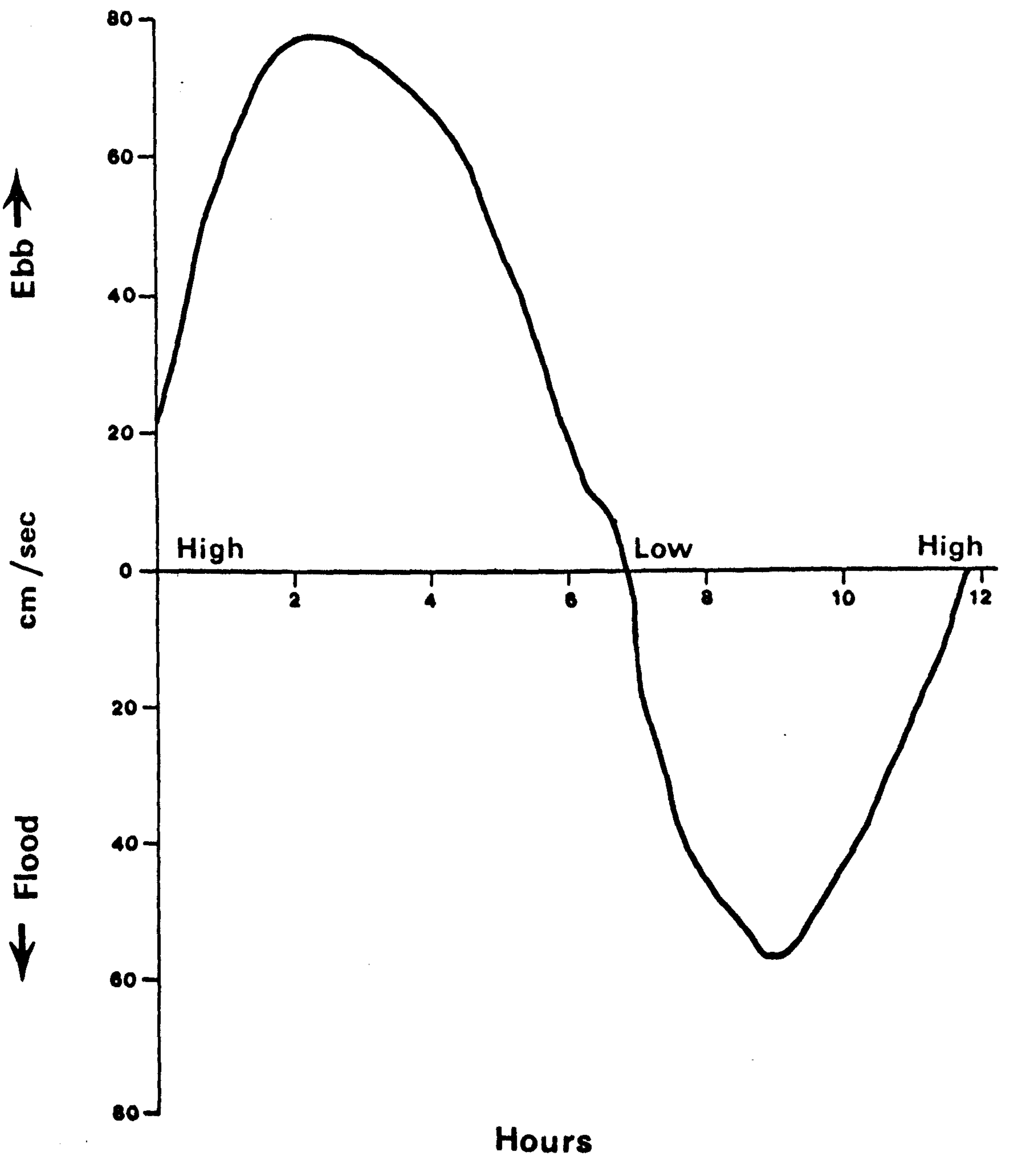
TIDAL STATION 2

FIGURE 38



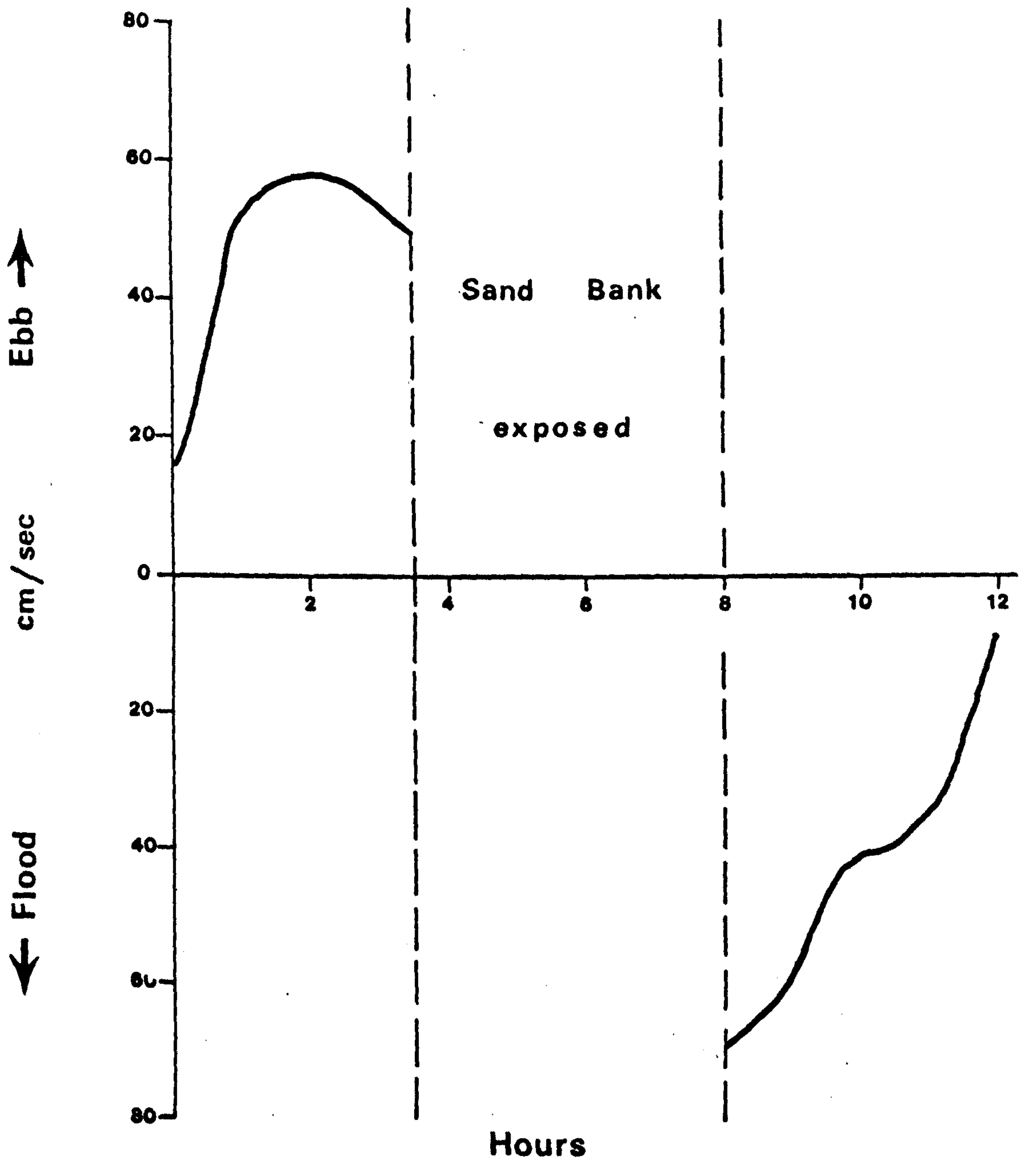
TIDAL STATION 3

FIGURE 39



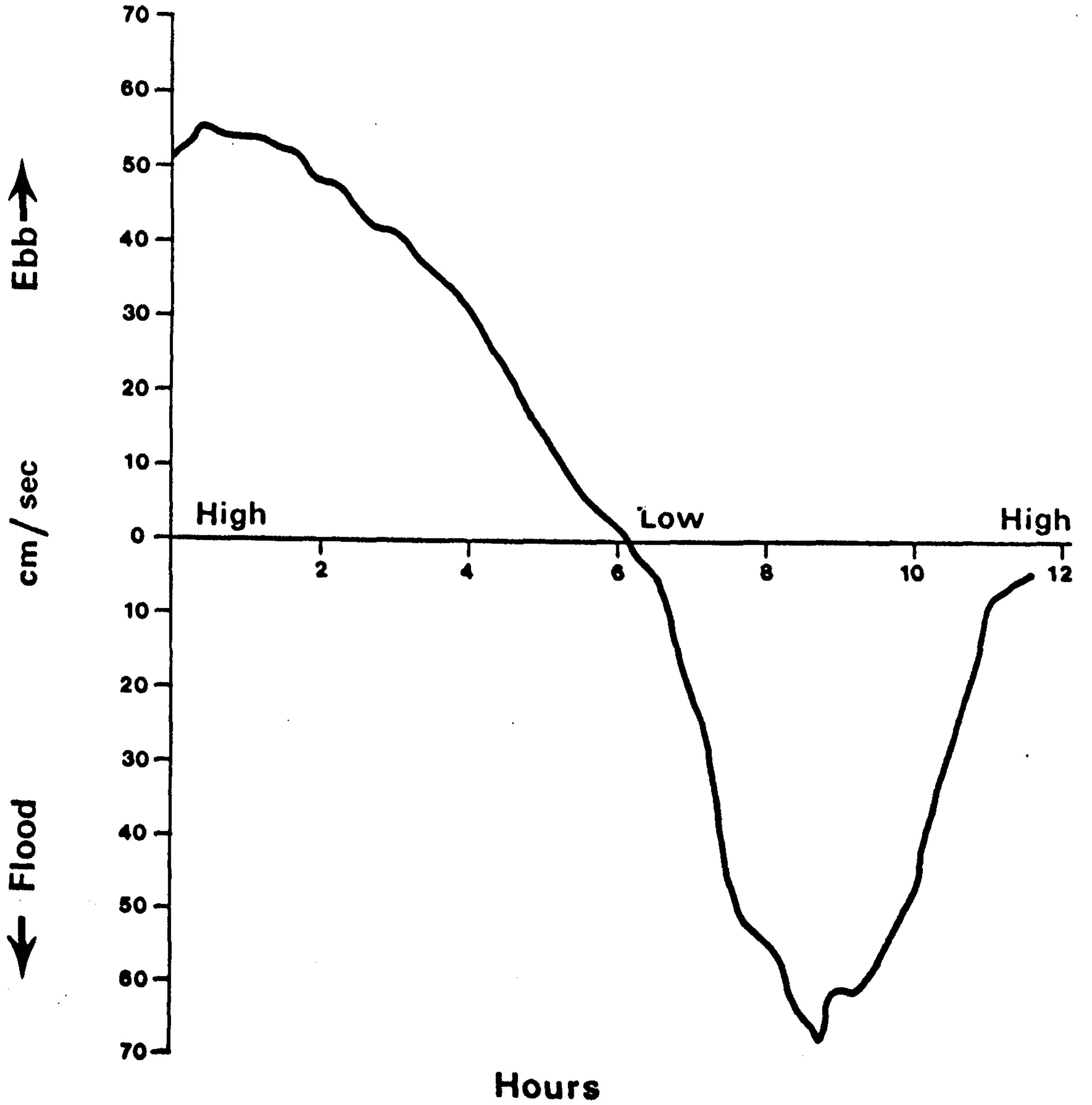
TIDAL STATION 4

FIGURE 40



TIDAL STATION 5

FIGURE 41



The turn of the tide was approximately ½ hour after low water. At tidal station 3, located in the Boston Deep, the peak ebb velocity was 78 cm./sec. 2¼ hours after high water and the peak flood velocity was 55 cm./sec. 3 hours after low water. Again the turn of the tide was delayed by ¾ hour after low water. At tidal station 5, situated in the channel between the Skegness Middle and the shoreline, the peak ebb velocity was 55 cm./sec. 1 hour after high water and the peak flood velocity was 66 cm./sec. 3 hours after high water. The turn of the tide at this location was at the time of low water.

At tidal station 2, situated over the Inner Knock, the ebb velocity reached a peak of 71 cm./sec. 3½ hours after high water immediately before the emergence of the sandbank. A maximum flood velocity of 34 cm./sec. was recorded immediately after submergence of the sandbank by the rising tide. At tidal station 4, located over the Outer Knock, a maximum ebb velocity of 58 cm./sec. was recorded 2 hours after low water and 1½ hours before the emergence of the sandbank. A peak flood velocity of 68 cm./sec. was recorded immediately after submergence of the sandbank 2 hours after low water.

DIRECTION OF FLOW OF TIDAL CURRENTS

Measurement of the direction of flow of surface water during a full tidal cycle revealed two patterns of water movement dependent on the location of the tidal station relative to sandbanks and channels. At tidal stations 2 and 4, located over sandbanks, tidal flow was divergent from the long axes of the sandbanks at shallow depths of water flow. At tidal station 2 tidal flow was parallel to the long axis of the Inner Knock, that is northerly, during the early stages of the ebb tide but diverged by 15 degrees in a north westerly direction immediately before the emergence of the sandbank. During the flood tide tidal currents flowed in a consistently southerly direction. At tidal station 4 tidal currents were northerly on the ebb tide but immediately after submergence on the flood tide diverged in a south-westerly direction by 20 degrees from the long axis of the western limb of the Outer Knock. As water flow deepened towards the end of the flood tide the direction of flow became progressively southerly.

At tidal stations 1, 3 and 5, situated in channels, the flow on the ebb tide was in a northerly direction and in a southerly direction during flood tides. A confused pattern of water flow was monitored for approximately 15 minutes either side of the turn of the tide.

DISCUSSION

It has been established that tidal currents in the study area are competent to transport available sediment for a minimum of 75% of the time.

Klein and Whaley (1972) and Boothroyd and Hubbard (1974) measured mean tidal current velocity curves for complete tidal cycles in the Bay of Fundy and the Parker estuary of Massachusetts respectively. Both studies used a measured asymmetry of maximum flow velocities on ebb and flood parts of the curves to predict migration directions of bedforms and net sediment movement directions. In the Bay of Fundy the beginning of megaripple migration was recognised by "boiling" of the sea surface and found to coincide with a mean velocity of approximately 60 cm./sec. On the basis of a comparison of the total times mean velocities exceeded this threshold on ebb and flood tides a prediction was made of the net sediment movement direction. In areas with low velocity asymmetry in the Parker estuary sandwaves were found to be symmetrical whereas areas with high maximum ebb velocities compared with maximum flood velocities were found to have ebb-oriented sandwaves. In both these study areas the asymmetry of tidal flow only found expression in terms of maximum flow velocities during ebb and flood tides. In the Skegness area the asymmetry finds expression not only in terms of maximum flow velocities but also in terms of the duration of ebb and flood tides. Such time asymmetries may invalidate the use of the relationships established in the above studies in the Skegness area. Furthermore sediment movement is not related to mean flow velocity in the water column but to boundary shear stress which is related to the rate of change of velocity with depth, itself largely independent of mean flow velocity. Because of these considerations it was thought injudicious to predict net sediment movement directions on the basis of the tidal current velocity curves.

However it is important to note that at all tidal stations situated in channels ebb tidal flow had a longer duration than flood tidal flow. Such a relationship suggests an overall dominance of ebb or northerly movement of sediment in the area. This agrees with the theory of Robinson (1964) that sediment can only migrate out of the Wash embayment along ebb dominated channels either at Gibraltar Point on the western side of the Wash or close inshore at Hunstanton on the eastern side of the Wash. The central channel of the Wash, the Well Deep, is a flood channel along which sediment is transported into the embayment.

A more realistic approach to the evaluation of the direction of sediment movement on the basis of measurement of tidal currents is to consider the bedload transport indices for each tidal station. Observations of direction of water movement show that during ebb tides water flows in a northerly direction and during flood tides in a southerly direction parallel to the long axes of the channels at tidal stations 1, 3 and 5. Of the three tidal stations located in channels two suggest a net movement of sediment in a flood or southerly direction the third in an ebb or northerly direction. In the Wainfleet Swatchway and the channel between the western limb of the Skegness Middle and the shoreline the southerly residuals of bedload transport index are relatively small, 24.29 and 138.2 respectively, sediment moving in opposed directions at approximately the same rates on ebb and flood tides, the latter being slightly dominant. In contrast the ebb bedload transport index in the Boston Deep is approximately three times greater than the flood bedload transport index in this channel suggesting a relatively large movement of sediment in a northerly direction. The fact that this residual ebb bedload transport index is so large, 572.35, compared with the residual flood bedload transport indices in other channels supports the notion that the dominant sediment movement direction in the area is northerly.

At tidal station 2 located over the Inner Knock sandbank the residual bedload transport index was 520.75 and was in an ebb direction. At tidal station 4 located over the Outer Knock the residual bedload transport index was 521.31 and was in a flood direction. Direction of water movement at these locations was found to vary depending on the depth of water flow. At both tidal stations water movement direction was oblique to the long axis of the sandbank, in the case of tidal station 2 just before emergence and in the case of tidal station 4 just after submergence. Since maximum bedload transport indices were recorded at these localities at the periods when water flow was oblique to the sandbank long axis it is probable that net sediment transport is also oblique to the long axis of the sandbank. In the case of the Inner Knock sediment transport will be in a north-north westerly direction across the sandbank whereas on the western limb of the Outer Knock sediment transport will be in a south-south westerly direction across the sandbank.

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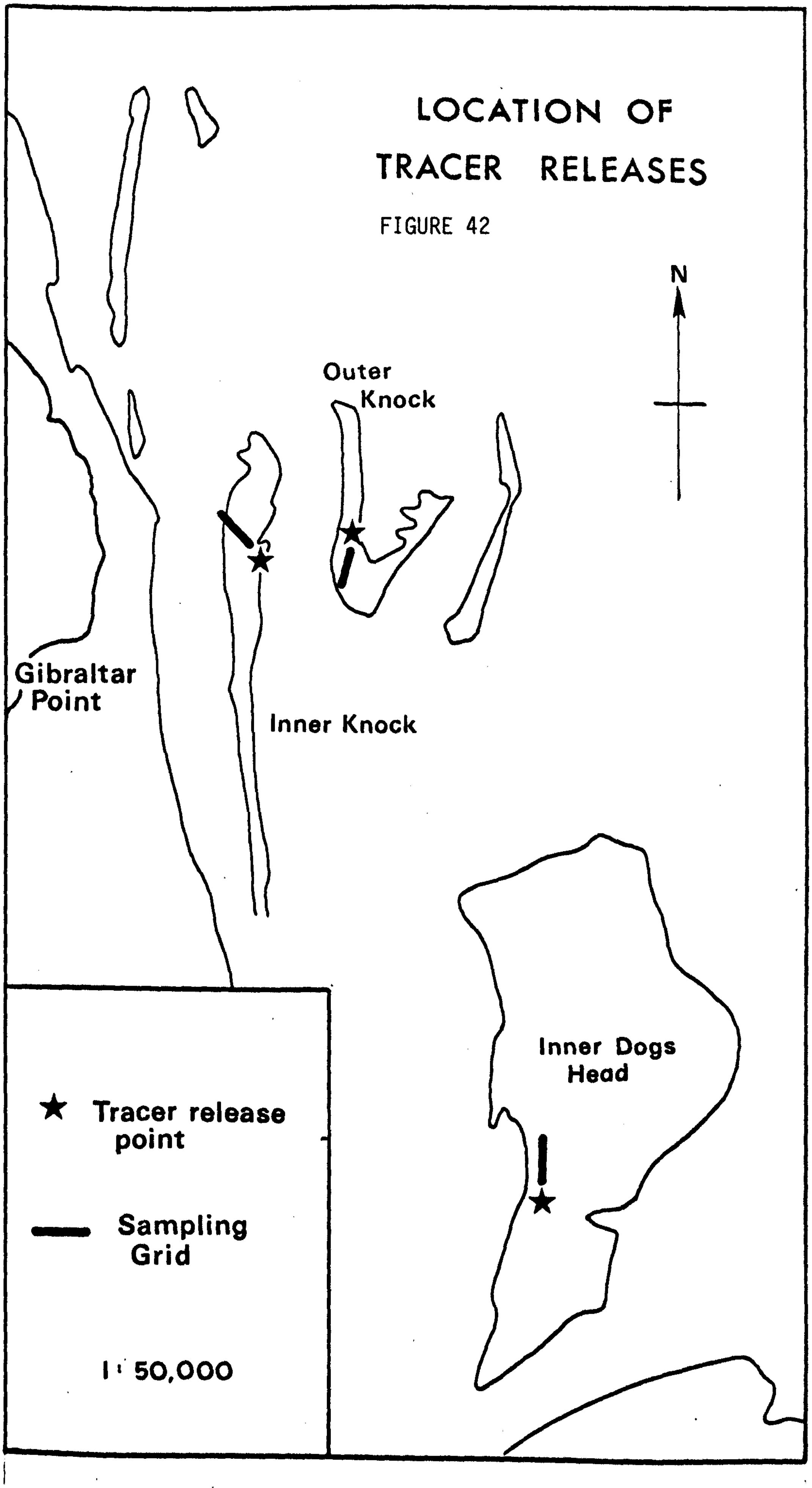
CHAPTER SEVEN

SEDIMENT TRACER EXPERIMENTS

Sediment tracers are the only direct measure of sediment movement, both in terms of direction and quantity, used in this thesis. Tracers must be easily recognisable marked sand grains which have the same hydrodynamic response to moving water as the natural population of sand grains being studied. Marked sand grains are introduced, with as little disturbance as possible, into the natural sediment system. Since the hydrodynamic reponse of marked grains is the same as the natural population of sand grains the entrainment, transport and deposition of marked grains will occur at the same time and at the same rate as the natural grains.

After a period of time during which the marked grains have been subject to migration, the natural sediments, containing the marked sediments, are sampled to determine the areal distribution of marked sand grains. The dispersion pattern of marked sand grains will be the same as that of the natural sand grains. The period of time allowed for the migration of the marked grains will depend on the information required from the experiment, the resistance of the marking agent to abrasion and the dilution rate of marked grains beyond levels where the concentrations of marked grains is not sufficient to define dispersion patterns.

Three tracer releases were made on the sandbanks in the study area. The locations of the release points are shown on Figure 42. Release 1 was situated on the Inner Knock at the location of tidal station 2 and release 2 was situated on the Outer Knock at the location of tidal station 4. Releases 1 and 2 were both in areas of megaripple trains. Release 3 was made on the sandwave train on the Inner Dogs Head for comparison of sediment migration rates with the areas dominated by megaripples.


LOCATION OF
TRACER RELEASES
FIGURE 42
N
Outer
Knock
Gibraltar
Point
Inner Knock
Inner Dogs
Head
Tracer release
point
Sampling
Grid
1: 50,000

There are three methods commonly used for the quantitative determination of rates of sediment transport in the marine environment (Ingle and Gorsline, 1973) :-

a. The time integration method. This method involves the measurement of the variation of concentrations of tracer material with time at a given point downstream of the tracer source. The mean velocity of tracer grains is established by noting the time elapsed between tracer injection and the moment of peak tracer concentration at the downstream sampling point. Limitations of this method are related to the possible sorting of sediment by the flowing medium (Vernon, 1966) and the lack of three dimensional measurement of tracer concentration since only the surface layers of sand are monitored.

b. Dilution method. Tracer grains are injected at a constant rate at a point source over a time period sufficient for the stabilization of the rate of tracer movement. The dilution of tracer grains is measured at a location downstream of the point source (Crickmore, 1967). Limitations of this method include the assumption that negligible loss of particles will occur in any direction other than that of the sampling location.

c. The space-integration method. This method involves the release of a known quantity of fluorescent grains at a point source followed by a periodic areal sampling of the surrounding areas to establish the areal concentration of the tracer grains. The drawing of isolines or contours on the distribution of tracer concentration allows the motion of the centroid of tracer concentration to be determined. An average velocity of tracer grain movement is established by measuring the variation in distance of the centroid from the point of tracer release over a given interval of time. This method was successfully applied to the measurement of longshore transport on beaches on Baja California by Komar and Inman (1970). To quantitatively determine the amount of tracer movement the depth of disturbance of the sediment surface must be determined to establish a three dimensional measurement of tracer concentration.

The space-integration method was adopted in this study largely for the practical reasons of safety and ease of sampling of tracer concentrations at times when the sandbanks were exposed at low water. Tracer material was deposited on a sandbank at low water (Figure 43) and the adjacent area sampled, again at low water, after two complete tidal cycles, 24 hours. This sampling plan allowed for boat use only during daylight hours.

FIGURE 43 TRACER RELEASE

TRACER MATERIAL

To accurately record the movement of seabed material the tracers should have the same hydrodynamical properties as the migrating material, particularly in terms of specific weight, grain size distribution and particle shape.

Two types of particle labelling have been developed which satisfy these criteria. Firstly artificial radio-active tracers have been successfully used in France (Courtois, 1973), Germany (Pahlke, 1973) and the United Kingdom (Smith, 1973). Ground glass is usually employed as the activated medium although natural sands have been successfully radiated (Crickmore, 1967). Secondly, sand grains have been labelled using fluorescent organic dyes (Zenkovitch, 1962). Sand grains labelled in this way have been successfully employed in both beach (Ingle, 1966) and offshore (Jolliffe, 1963) environments. On the grounds of cost and safety this method of labelling was employed in the present study.

The dye is bonded to the grains using a medium of air curing plastic and organic solvent which ensures chemical stability in seawater. Several dyes are commercially available which include Uvitex (fluoresces blue), Eosine (fluoresces Yellow) and Rhodamine (fluoresces red). Use of colours within the blue region can cause difficulties because some skeleton remains in coastal sediments also fluoresce blue (de Vries, 1973).

Yasso (1962) conducted experiments to determine the detection rate and thickness of coating of the grains. It was found that coated grains were discernable in concentrations as low as 1 in 10^6 particles and the coating increases the grain radius by as little as 300 millimicrons. Ingle (1966) assessed the hydrodynamic effect of coating grains using Emery settling tube analysis of dyed and undyed sand samples. These experiments indicated that the hydraulic properties of the grains were not affected by the dyeing process.

Ideally sand to be labelled should be collected, dyed, and returned as quickly as possible to the proposed release point.

In the present study it was proposed to release a minimum of 50 kg. of labelled sand at each selected site. Coating of such large quantities of sand is impossible in the field, requiring laboratory facilities and a considerable hardware investment. For example, the coating technique of Russell (1960) is probably the most appropriate for use in the marine environment. This technique employs aerolite resin and acid hardner as the bonding medium, which needs 2 to 3 days curing time and subsequent treatment in a jaw crusher, Spruemaster and sieves.

Consequently a compromise was reached whereby commercially prepared dyed sand was obtained from British Industrial Sands Ltd. The hydrodynamic properties of this material was compared with sand from the proposed release points.

Samples of grains from the sandbanks and the commercially prepared material were examined under microscope and both found to be sub-rounded in the shape classification of Shepard and Young (1961). Sandbank samples were found to have a slightly higher specific weight than the coated material, probably indicting a higher proportion of heavy minerals. However, the differences were so small that the coated material can be assumed to have the same hydrodynamic response as the local material.

The proposed release point for the fluorescent sand was marked with a stake, located on aerial photographs, and a sand sample taken one week before the scheduled commencement of the experiment. The sand sample was sieved and the size fractions determined in the laboratory. The fluorescent sand was also sieved, divided into size fractions, and to ensure maximum compatability, subsequently matched with the sample taken from the release point.

Further sand samples were taken from the release point at the time of the release of the fluorescent sand. These samples were sieved and the size fraction distribution compared with the original samples. In no case was the change, over the one week preparation period, found to be significant.

TRACER RELEASE

To facilitate ease of release and subsequent sampling of tracer distribution all release points were selected at locations on the sandbanks which were dry for at least 3 hours during spring tides.

The tracer material was transported to the release point in 10 kg. bags. A small amount of wetting agent, domestic liquid detergent, was added to each bag together with sufficient seawater to wet all grains. This expedient ensured that no grains entered suspension prematurely or floated when subsequently covered by water. No grains,therefore, would be carried at abnormally high velocities by tidal currents.

The tracer material was spread evenly over the sand surface at the release point to a maximum depth of 1 cm.

SAMPLING METHODS

The distribution of fluorescent sand was sampled after 24 hours, that is, two complete tidal cycles. The 24 hour sampling period was chosen for logistical and safety reasons, particularly the desire for boat use only during daylight hours. Samples were collected on a 10 m. grid which was deployed, using thin wooden stakes, at the time of release of the tracers.

Any sampling device used must collect samples of uniform volume or area to allow quantitative comparisons of tracer concentration at each sampling point (Ingle, 1966). Several sampling methods have been developed which include constant depth corers recovering constant volumes (Wright, 1962) and grease-coated plastic cards representing constant sample area (Ingle, 1966 and Jolliffe, 1963). Both methods were employed in the present study but were found to be unsatisfactory for two reasons :-

1. Difficulty was experienced in taking constant sized samples using both techniques. The grease-coated cards collected uneven samples particularly on surfaces with high densities of ripples which are ubiquitous on the sandbanks in the area. Pebbles and shell fragments in the sand frequently frustrated attempts to use a coring device.

2. Experiments to determine the depth of disturbance of sediment by tidal currents were conducted simultaneously with the tracer experiments. The method employed was that detailed by King (1951). Holes were made in the sand to depth of 15 cm. using a pointed

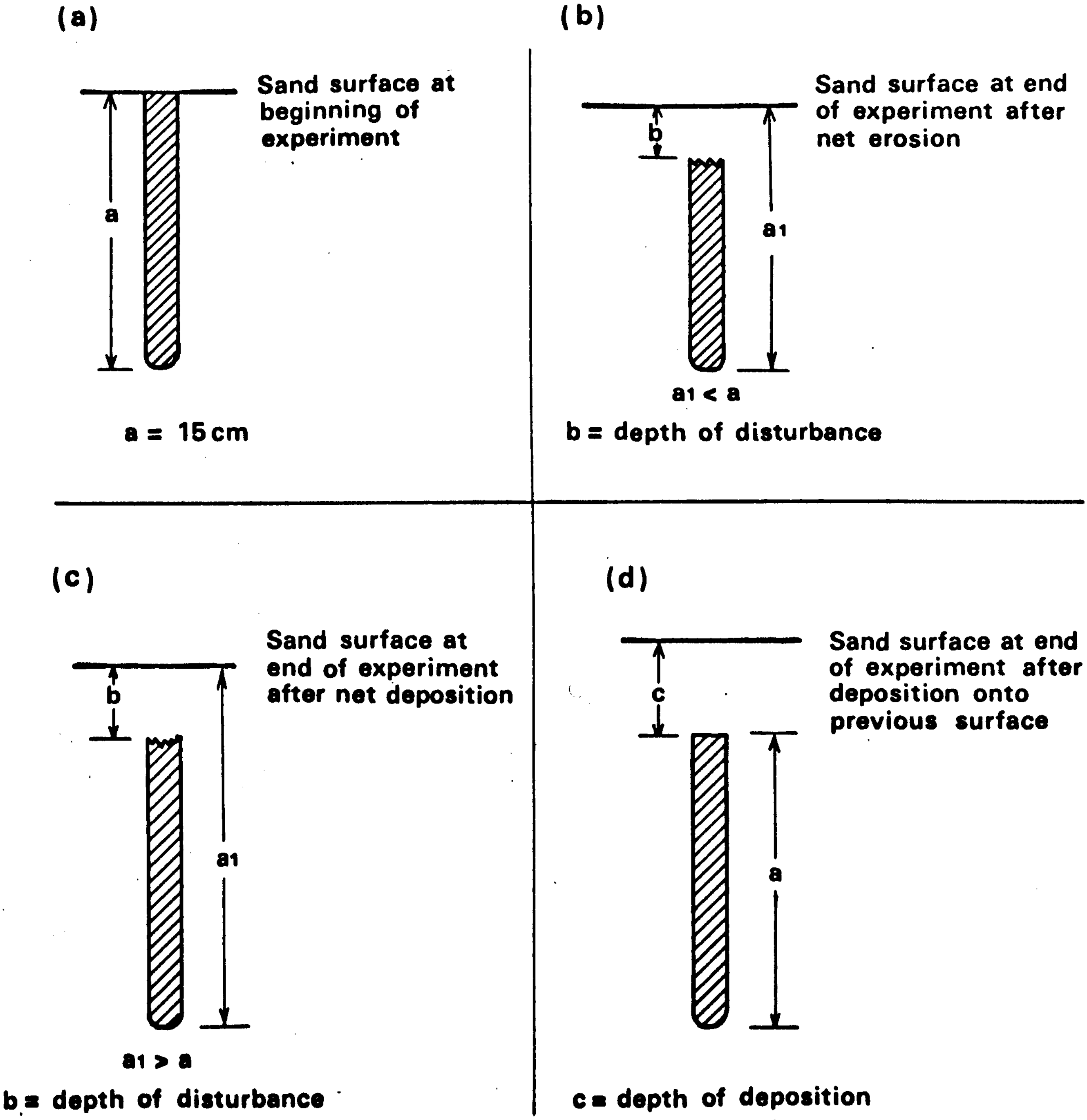
1 cm. dowel at the grid intersections marked by wooden stakes. The holes were filled with sand dyed with black waterproof ink. Figure 44 illustrates the configurations of cores relative to the sand surface which were found on the sandbanks after two complete tidal cycles. All tracer experiments were conducted in areas dominated either by sandwaves or megaripples. The sedimentological implications of the core configurations will not be discussed further in this thesis but would provide a fruitful avenue for further reseach.

The depth of disturbance of sand grains was found to vary systematically in relation to the morphology of sandwaves and megaripples. (Figure 45) Fluorescent sand grains were found at all levels and were not distributed randomly within the disturbed layer, although it proved impossible to establish any systematic variation in the distribution. Consequently, it was considered necessary to sample for fluorescent grains to a depth coincident with the known depth of disturbance at different locations on each bedform. Equal area surface sampling or constant volume core sampling would introduce undesireable bias into the sampling plan.

The sampling technique adopted involved the removal of the disturbed layer at the grid intersections over an area of 100 sq. cm. using a stainless steel laboratory shovel. This technique involved the collection of samples of unequal volume, a problem overcome in the counting method detailed below.

CORE CONFIGURATIONS FOR DEPTH OF DISTURBANCE EXPERIMENTS

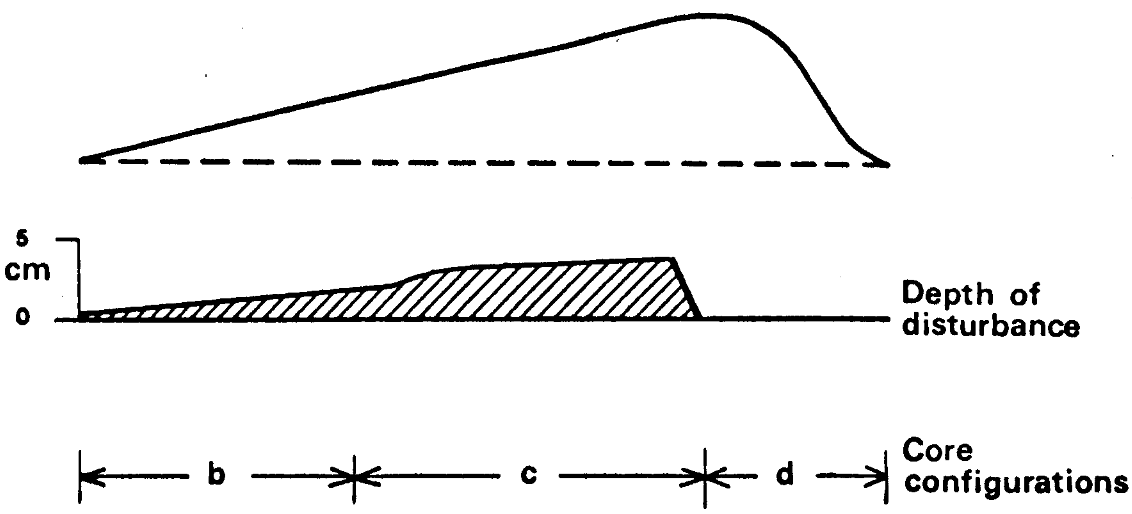
FIGURE 44



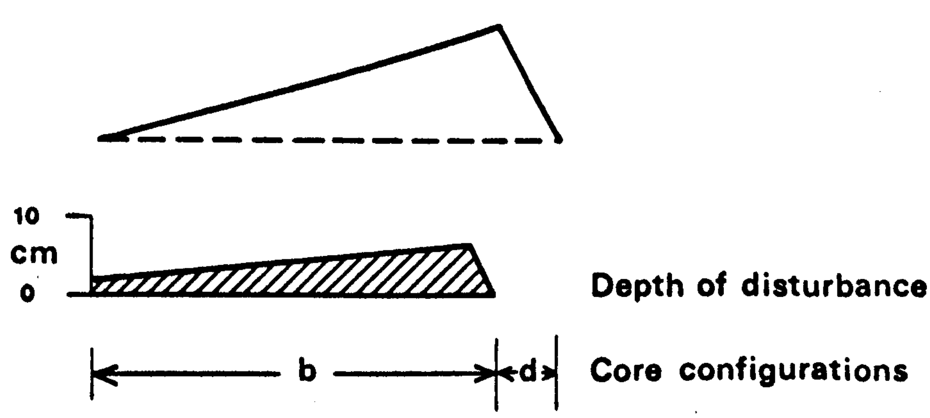
DIAGRAMATIC REPRESENTATIONS OF THE RESULTS OF THE DISTURBANCE EXPERIMENTS

FIGURE 45

(a) Sand Waves



(b) Mega-ripples



Samples were labelled and returned to the laboratory in plastic bags.

DETERMINATION OF TRACER CONCENTRATION

Labelled grains are easily distinguished from others when exposed to ultra-violet light. Inspections of samples were made using a Hanovia chromatolyte-type ultraviolet lamp. For tracer concentrations to be comparable between samples the number of fluorescent grains must be determined per unit area, volume or weight. The counting technique developed involved the determination of grains per unit weight.

On return to the laboratory the samples were air dried and weighed to the nearest 1/100 gram. Electronic counting techniques (de Vries, 1967) have been developed which will count all fluorescent grains in a sample. Such instrumentation is expensive and could not be used in the present study. Manual counting of all fluorescent grains in a sample is extremely time consuming and therefore not practical.

Ideally, a representative sample should be taken from the field sample, weighed, spread over a surface to a maximum of one grain thickness and exposed to ultra-violet light for counting of fluorescent grains. The technique developed satisfies these criteria.

Non-reflective black rice paper was cut into 20 cm. x 20 cm. squares and coated with 3M Spray Adhesive 77 (Fig. 46). The field sample was then sprinkled onto the coated paper and time allowed (30 seconds) for the adhesive to cure. Excess sand was then shaken from the coated paper, collected, weighed and the

FIGURE 46

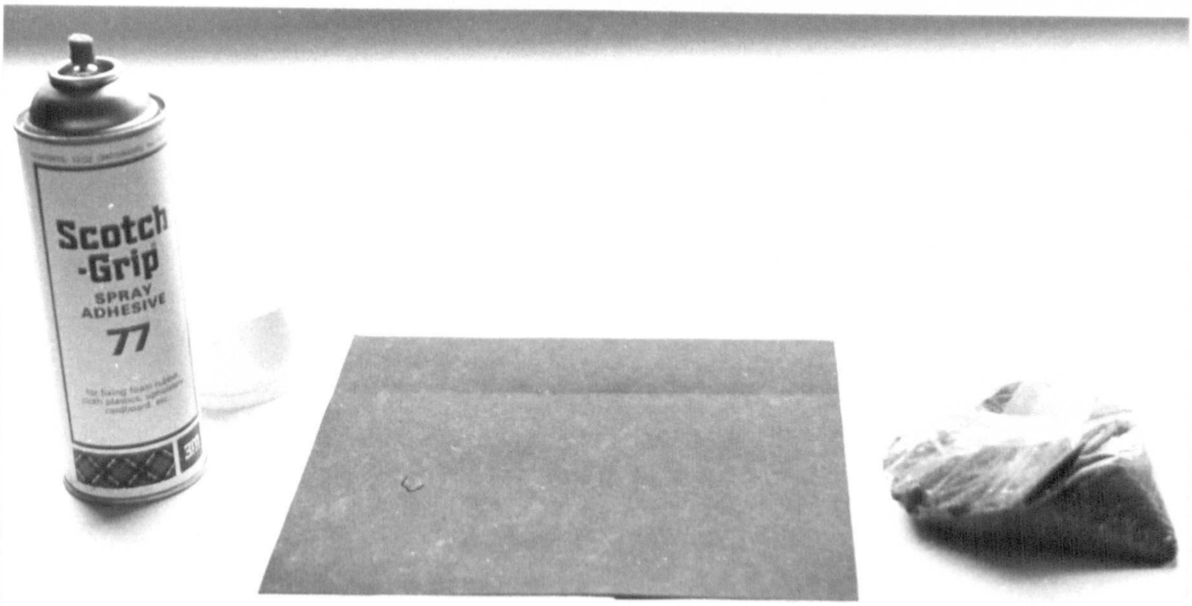


FIGURE 47

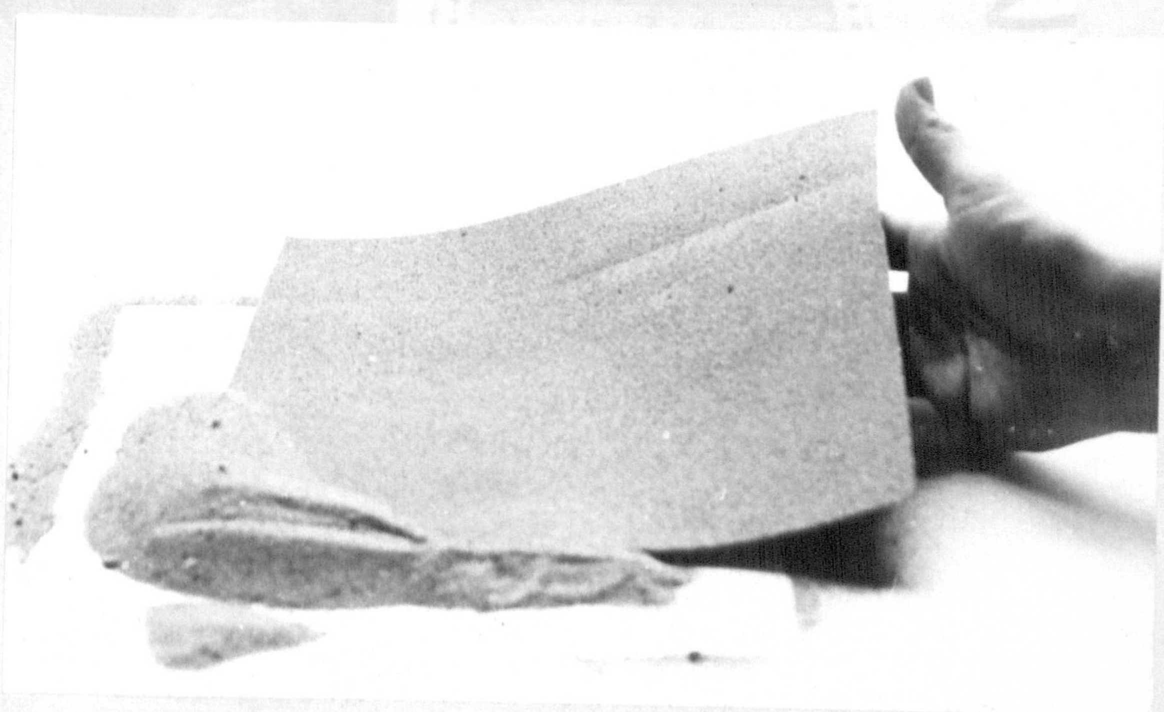
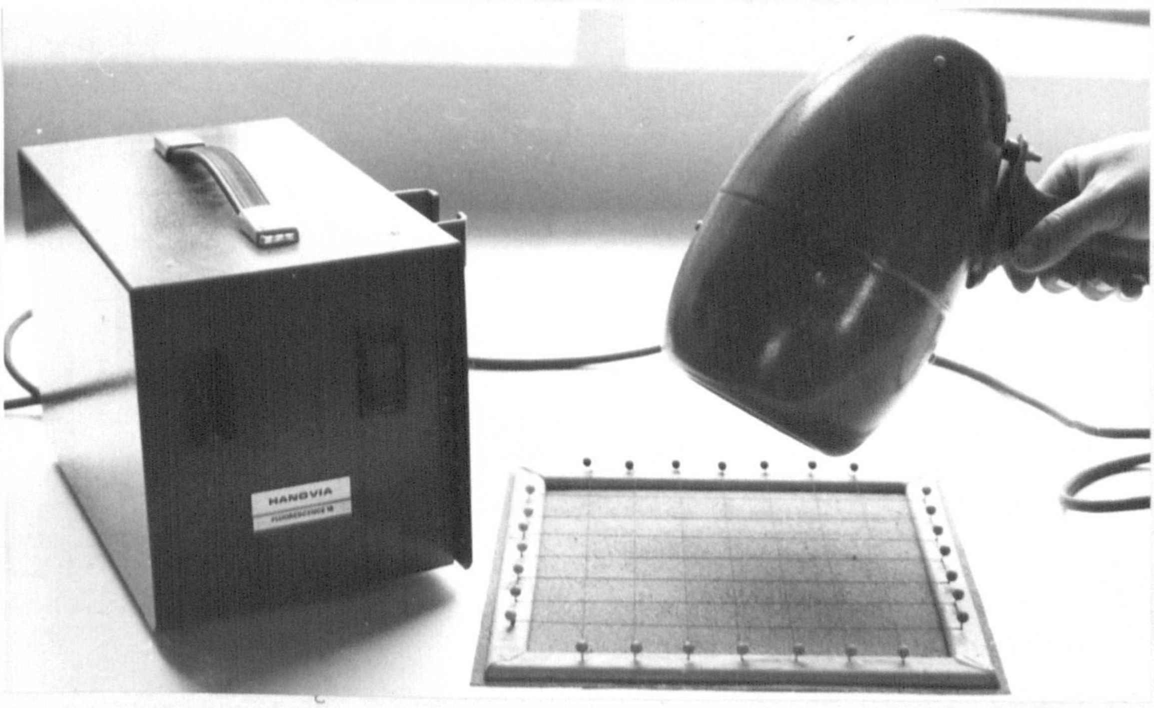


FIGURE 48



amount of sand retained on the paper was determined. (Figure 47) The coated paper was then exposed to ultra-violet light (Figure 48) to determine the number of fluorescent grains per gram of sample.

Repeated coatings of sand from one field sample showed that one coating could be taken as representative of the whole sample, maximum differences between coating being 8% of the grains counted on each card.

MAPPING THE AREAL DISTRIBUTION OF TRACERS

All three sampling grids were deployed with the release points of the tracers at the centre of the 40 m. axis which was normal to the direction of sediment movement anticipated on the basis of bed-form orientations (Figure 42). The axis of the grid parallel to the anticipated direction of sediment movement was 100 m. in length. A total of 55 samples were taken from each grid using the methods described above.

The concentration of tracer material at each grid intersection was then determined and assigned grid co-ordinates. Since manual contouring of tracer concentration would lead to an inevitable introduction of bias into the resulting dispersal pattern a computer contouring programme described in Davis (1973, p.310) was employed. This programme uses a simple algorithm for printing contour maps on a line printer assuming that the grid spacing of the sampled population corresponds with the mosaic established by the line printer carriage. The line printer used for mapping tracer concentrations prints ten characters per inch horizontally and six lines of characters per inch vertically and, therefore, every square inch of the finished map will contain 60 printed characters.

The two axes of the sampling grid were scaled so that the 40 m. axis corresponds to 60 characters horizontally and the 100 m. axis corresponds to 90 character lines vertically, 1.5 inches, therefore, representing 10 m. on each axis of the finished map. Since the line printer mosaic is much more dense than the sampling grid, values of tracer concentration at each point on the line printer mosaic are estimated from the six nearest sampling grid intersections by a distance weighted average algorithm. This interpolation of values creates a smoothed map of tracer distribution.

The line printer map is composed of selected line printer characters which correspond to specified class intervals. Any number of intervals and boundary values between intervals can be selected within the programme. Several tests were made to discover the number of intervals and boundary values which gave the best visual impression of tracer distribution for the three releases. Nine intervals were selected ranging from greater than 0.2 grains/gm. to less than 0.002 grains/gm. with 8 boundary values at 0.002, 0.004, 0.008, 0.016, 0.03, 0.06, 0.1 and 0.2 grains/gm. For visual clarity the boundaries, or contours, between intervals "shaded" by line printer characters were traced from the line printer maps. The resulting contour maps of tracer concentration, which have also been reduced from the original line printer scale, are shown as Figures 49 to 51 for releases 1 to 3 respectively.

DISCUSSION

Most studies involving sediment tracers in the nearshore zone have employed radioactive tracers since tracer concentrations can be monitored remotely, at very low levels, using Geiger counters

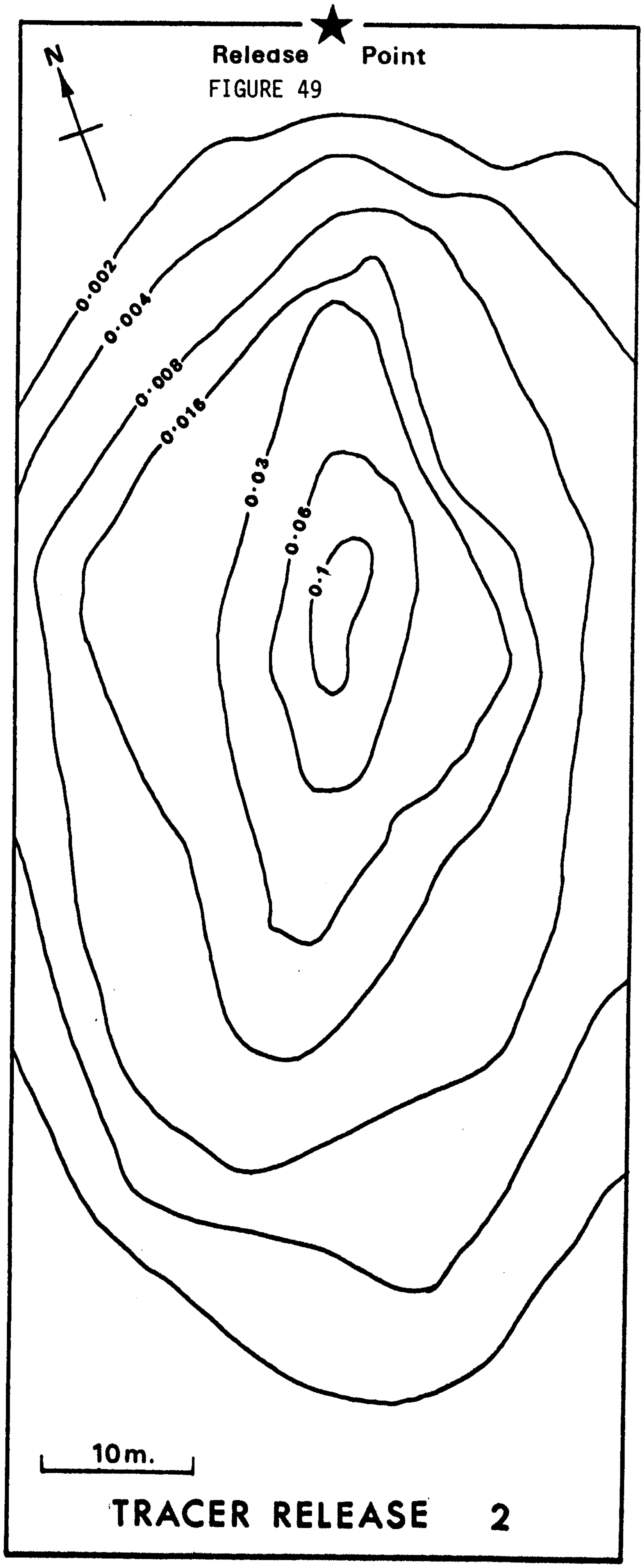
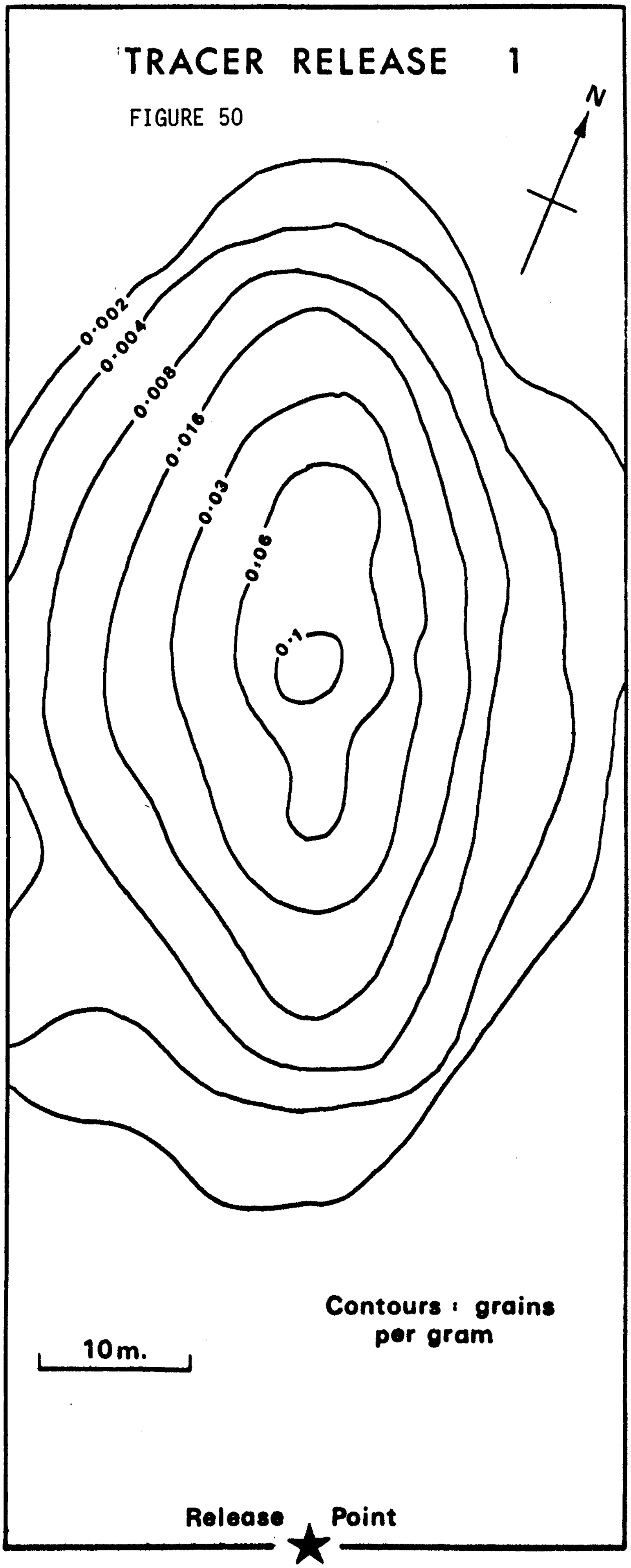
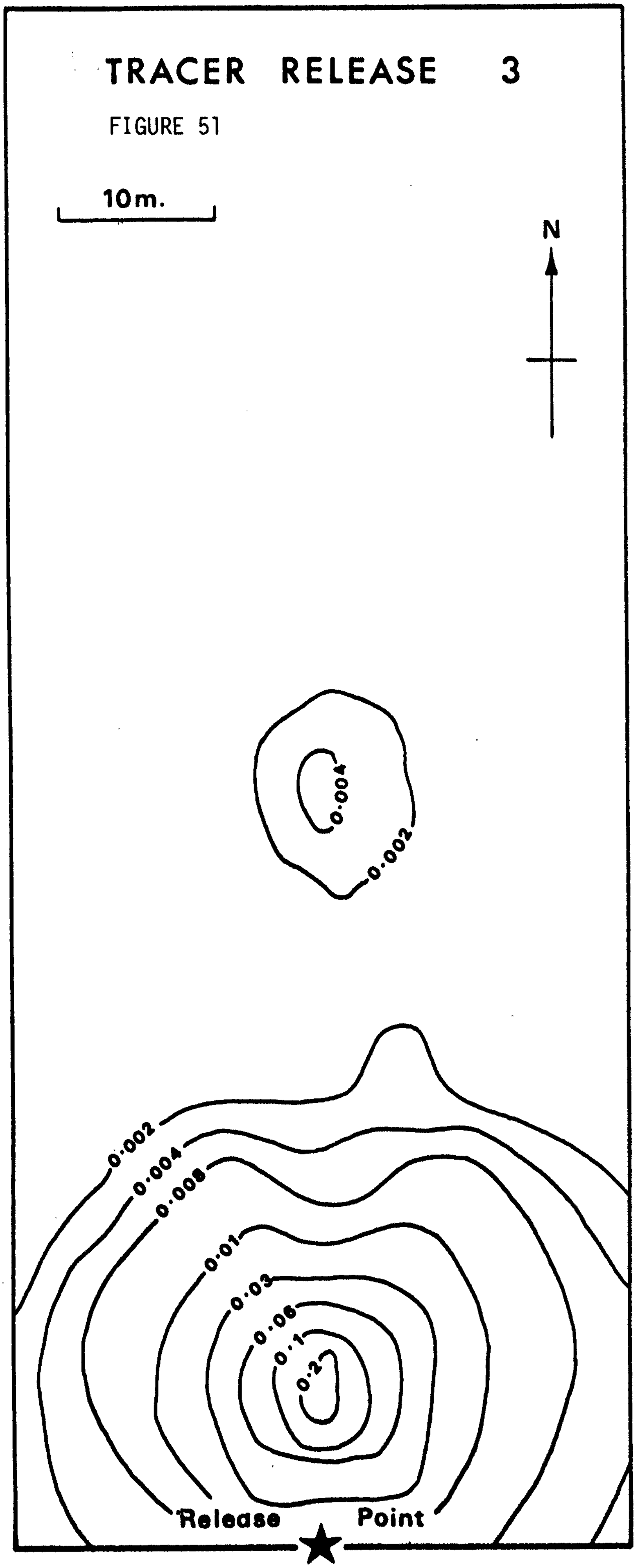

Release Point
N
0.002
0.004
0.008
0.016
0.03
0.06
0.1
10m.
TRACER RELEASE 2

FIGURE 49


TRACER RELEASE 1
FIGURE 50
N
0·002
0·004
0·008
0·016
0·03
0·06
0·1
Contours : grains per gram
10m.
Release Point


TRACER RELEASE 3
FIGURE 51
10m.
N
0·004
0·002
0·002
0·004
0·008
0·01
0·03
0·06
0·1
0·2
Release Point

and scintillation detection methods (Courtois, 1973). Radioactive tracers have been used to show the migration direction of sand off the coasts of East Anglia (Reid, 1958) and Holland (Morra et. al., 1961) and local sand migration directions amongst sandbanks in the German Bight (Samu, 1968). There are few studies which have successfully employed fluorescent tracers as indicators of sediment movement in the nearshore zone, probably because of the difficulty of sampling tracer distribution after movement, particularly in subtidal areas. Financial considerations, however, dictated the use of flurescent tracers in the study area.

Jolliffe (1963) conducted a study of sand movement on the subtidal Lowestoft sandbank using fluorescent tracers. Marked sand grains were released at four locations, each location being represented by sand of a particular colour, and sampled using grease coated cards at the northern tip of the sandbank to ascertain the local source of material.

A large degree of particle dispersion was found to occur at each injection site and dispersion appeared to have been in all directions simultaneously. Movement of sand grains was considered to occur in a significant thickness of mobile sediment on the sea bed and en masse, that is as a cloud, rather than a steady trickle of surface particles. The general sediment circulation around the sandbank appeared to consist of a strong northward drift along the landward face and a slight northward drift along the seaward face.

After 21 days sand particles had travelled at least 3.2 km. northwards and 2.4 km. southwards from the injection sites, representing daily migration rates of 152 and 114 m. respectively.

In the Skegness area the migration rates for the centroids of tracer dispersion patterns varied from 58 m. in 24 hours at the location of tracer release 1 to 10 m. in 24 hours at the location of tracer release 3. At the location of tracer release 2 the migration rate was 39 m. in 24 hours. All these migration rates are significantly lower than those monitored on the Lowestoft Bank. However, the derivation of the figures from the Lowestoft Bank is not clear and they may not represent the speed of movement of the centroid of the tracer cloud, the parameter usually taken as a measure of the speed of movement of sediment tracers. These figures may not therefore, be comparable with those determined from tracer studies in the Skegness area.

The grids for sampling tracer dispersion patterns were all established with their long axes parallel to the direction of sediment movement anticipated on the basis of bedform orientations. (Figure 42). In all three cases the movement of the centroid from the release point was parallel to the long axis of the sampling grid (Figures 49 , 50 and 51) confirming the directions of sediment movement predicted from bedform orientation in Chapter 5.

Considerable lateral dispersion, that is movement perpendicular to the major axis of sediment movement, has also occurred at the tracer release sites. In all cases concentrations of tracers of 0.004 grains/gm. of sampled sediment were registered at a distance of approximately 20 m. either side of the major axis of sediment movement. This lateral movement of sediment is probably related, at least in part, to lateral eddies associated with flow separation over bedforms (Allen, 1968).

At tracer release 3, located in an area of sandwaves, two centroids of tracer dispersion are apparent, one much smaller than the other (Figure 51) and 40 m. apart. The separation of the centroids corresponds approximately to the wavelength of the sandwaves at the location of the tracer release. The double centroid and the spacing between the centroids suggests that sediment moves in a series of steps, or bursts, between bedforms.

Centroid movements at tracer releases 1 and 2 were 54 m. and 39 m. in 24 hours, being respectively 5.4 and 3.9 times greater than the movement of the larger centroid at tracer release 3. Tracer releases 1 and 2 are located in areas where the dominant bedforms are megaripples where the depth of disturbance, probably corresponding to the thickness of the mobile layer, is approximately twice that associated with sandwaves (Figure 49) which are the dominant bedform at tracer release 3. It would appear, therefore, that in areas dominated by megaripples twice as much sediment is moving at speeds approximately four and five times greater than in areas dominated by sandwaves. That is, the rate of sediment transport associated with megaripples is between eight and ten times greater than the rate of sediment transport associated with sandwaves.

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CHAPTER EIGHT

SEDIMENT MOVEMENT
MODEL

As outlined in the Introduction the geomorphology of the nearshore zone can be considered in a framework of a process-response system. A descriptive sediment movement model will be constructed on the basis of the movement of sediment deduced from morphological and cascading subsystems, discussed in Chapters 3 to 7, which are integral parts of the process-response system. The model will be divided in two parts considering different aspects of the sediment flux, direction of movement and rate of movement.

DIRECTION OF SEDIMENT MOVEMENT

The Skegness Middle, Inner Knock, Outer Knock and Outer Dogs Head sandbanks were classified on the basis of morphology, both in terms of plan shape and cross-sectional asymmetry, as tidal current ridges. These depositional features have been shown to be related to the areal differentiation into either ebb or flood residuals of tidal current flow in the channels between the sandbanks. On the basis of the plan shape of the sandbanks it was possible to predict the net residual tidal flow in the contiguous channels.

The Boston Deep, the largest channel in the area, was classified as an ebb channel with a tidal flow residual and associated net sediment movement in an ebb, or northerly direction. The channel between the Inner Knock and the foreshore, the southern part of the Wainfleet Swatchway and the channel between the western limb of the Skegness Middle and the foreshore were classified as flood channels with associated net southerly movements of sediment. The northern part of the Wainfleet Swatchway, confined between the western and eastern limbs of the Skegness Middle, was classified as an ebb channel with associated net northerly movement of sediment. The two limbs and nose of the Outer Knock form a re-entrant into the northern extremity of the Boston Deep. The southerly closing channel between the limbs of the Outer Knock was classified as a flood channel with associated net southerly movement of sediment. The Parlour Channel, separating the Inner Dogs Head and Long Sand, was classified as a flood channel with a net south-westerly movement of sediment.

Measurement of the cascading subsystem of tidal current flow in the Boston Deep, the Wainfleet Swatchway and the channel between the western limb of the Skegness Middle and the foreshore allowed the computation of net bedload transport indices for sediment in these channels. In each of the three channels the computed index confirmed the net direction of sediment movement as predicted on the basis of the plan morphology of the sandbanks and channels. Measurement of the direction of movement of tidal currents in these channels also suggested that sediment movement in the channels was axial.

The cross-sectional asymmetry of the sandbanks was used to predict sediment movement relative to the sandbanks. The dominant movement of sediment is up and across the gentler side towards the steeper side of the sandbank. On the basis of this hypothesis sediment moves from the Boston Deep across the Inner Knock towards the Wainfleet Swatchway and from the Boston Deep across the Outer Dogs Head towards the Well Deep and the North Sea. The asymmetry of both limbs of the Outer Knock is such that the steeper sides of the sandbank face towards the Boston Deep. Sediment was, therefore, predicted to move in a southerly direction from the channel enclosed by the limbs of the sandbank, across the sandbank to the Boston Deep. The asymmetry of the Skegness Middle suggested movement of sediment from the channel between the western limb of the sandbank and the foreshore towards the channel enclosed by the western and eastern limbs of the sandbank, particularly at the southern extremity of the western limb. At the northern end of the Skegness Middle and at the middle section of the western limb of the sandbank sediment was considered to move from the channel enclosed between the limbs of the sandbank in a northerly direction.

An analysis of the orientations of bedforms on the sandbanks confirmed the general predictions of sediment movement relative to the sandbanks as described above. Bedform orientations also suggested that sediment movement across tidal current ridges is oblique to the long axis of the sandbank. In the case of the Inner Knock sediment movement was found to be in a north-westerly direction and in the case of the Outer Dogs Head sediment movement was found to be in a north-easterly direction. The orientations of bedforms on the limbs of the Outer Knock suggested that sediment movement was in a south-westerly direction on the western limb and a south-easterly direction across the eastern limb of the sandbank. Movement of sediment across the southern extremity of the western limb of the Skegness Middle was in a south-easterly direction.

Sediment tracer experiments on the Inner Knock and the western limb of the Outer Knock confirmed the predicted oblique movement of sediment across the sandbanks. Confirmation of the oblique movement of sediment at these locations was also given by net bedload transport indices computed from the measurement of tidal currents.

The Inner Dogs Head, in contrast to the other sandbanks in the area, was classified on the basis of morphology as an ebb-tidal delta. The major morphological feature of this sandbank was found to be a semi-circular topographic high. This topographic high was classified as a flood shield which protects the southern $2/3$ of the sandbank from modification by flood tidal currents which dominate the northern $1/3$ of the sandbank. With residual flood tidal currents to the south, the flood shield was thought to be an area of bedload convergence, an assumption which was confirmed by the very poor sorting of the sediments which comprise the shield. The orientations of the bedforms to the north of the flood shield were in a flood or southerly direction and suggested a convergence of sediment movement towards the central section of the flood shield. To the south of the flood shield two very distinct areas were defined on the basis of sediment size and bedforms. The central part of the sandbank was almost without bedforms and consisted of very fine sediments, both of these factors suggesting an area of weak tidal currents and little sediment movement. The western side of the Inner Dogs Head south of the flood shield was found to be occupied by a sandwave train which had an orientation in an ebb or northerly direction suggesting an associated northerly net movement of sediment.

The south-eastern corner of the Inner Dogs Head was found to be occupied by a small sandwave train which had an orientation in a south-westerly of flood direction. These bedforms were probably related to the flood tidal residuals in the Parlour Channel. A net south-westerly movement of sediment at this location was confirmed by a flood spit which extended from the Inner Dogs Head sandbank into the Parlour Channel.

RATE OF SEDIMENT MOVEMENTS

Relative rates of sediment movement were estimated from the type of bedform, the bedload transport indices and the sediment tracer experiments.

On the basis of the sediment tracer experiments and empirical evidence from direct observation in other areas sediment transport rates were thought to be of the order of ten times greater in areas of megaripples than in areas of sandwaves. The tidal current ridges are dominated by megaripples whereas the ebb-tidal delta is dominated by sandwaves. Sediment transport rates are, therefore, probably much greater on the tidal current ridges than on the ebb-tidal delta. The physical dimensions of megaripples are such that they could not be recorded on the echo-sounder equipment available for the present study. The presence or absence of megaripples on the floors of the channels is therefore, not known and a comparison between sediment migration rates in the channels and on the sandbanks cannot be made on the basis of bedforms.

Of the five tidal stations occupied for a complete tidal cycle three were located in channels and two were located on sandbanks. For the three tidal stations in channels the net bedload transport indices calculated for each location had widely different values. The Boston Deep, the largest channel in the area, had a net bedload transport index of 572.35 in an ebb direction which was 24 times and 4 times greater than the computed net flood bedload transport indices in the Wainfleet Swatchway and the channel between the Skegness

Middle and the foreshore respectively. Since the net bedload transport index in the Boston Deep is so much greater than the net flood bedload transport indices in the Wainfleet Swatchway and the channel between the Skegness Middle and the foreshore, and bearing in mind the fact that the Boston Deep is by far the largest channel in the area, it would appear that the net drift of sediment in the area is in a northerly direction.

The bedload transport indices computed for the tidal stations located on the sandbanks were very similar at both locations, a finding which was not surprising since megaripples were the dominant bedforms at each location. The rate of sediment transport recorded on the tidal current ridges was similar to that for the Boston Deep, suggesting relatively high rates of sediment transport over the sandbanks.

DISCUSSION

It would appear, therefore, that relatively high rates of sediment transport occur in a northerly direction in the Boston Deep and in a north-westerly direction across the Inner Knock and in a north-easterly direction across the Outer Dogs Head from the Boston Deep. This dominant northerly movement of sediment is counteracted in part by a general southerly movement of sediment from the channel enclosed by the limbs of the Outer Knock into the northern end of the Boston Deep. A southerly movement of sediment, of much smaller magnitude, also occurs in the Wainfleet Swatchway, again counteracting to a minor degree, the northerly movement of sediment in the Boston Deep. A similar minor southerly movement of sediment probably occurs on the seaward side of the Outer Dogs Head at the northern end of the Parlour Channel. The channel enclosed by the western and eastern limbs of the Skegness Middle has a net northerly movement of sediment which is counteracted by a southerly movement of sediment in the channel between the western limb of the sandbank and foreshore. A similar southerly movement of sediment probably occurs immediately seaward of the eastern limb of the Skegness Middle.

Swift (1975) suggested that tidal current ridges represent sediment traps of a high order of efficiency and are essentially closed cells of circulation of sediment. Such an argument probably applies to the tidal current ridges in the Skegness area. The large net northerly drift of sediment in the Boston Deep and across the contiguous Inner Knock and Outer Dogs Head sandbanks is counteracted by the smaller southerly drift of sediment in the Wainfleet Swatchway and the Parlour Channel. Since both the Wainfleet Swatchway and the Parlour Channel open in a southerly direction into the Boston Deep sediment will be re-introduced into the northerly drift in this channel, thereby creating a more or less closed circulation. Since relatively small amounts of sediment are transported in a southerly direction in the Wainfleet Swatchway and the Parlour Channel as compared to the northerly transport of sediment in the Boston Deep, the difference in transport rates probably represents the deposition of sediment or the storage capabilities of the tidal current ridges. Sediment deposited and stored within the tidal current ridges would be responsible for the growth of the sandbanks either in size or in a particular direction.

A similar more or less closed circulation probably exists around the Skegness Middle sandbank. A complication in terms of the circulation of sediment around this sandbank system occurs because the western limb of the sandbank is attached to the foreshore. Sediment moving south along the channel between the western limb of the Skegness Middle and the foreshore can either move in a south-easterly direction across the sandbank and be re-introduced into the northerly drift to seaward or can move in a south-westerly direction onto the foreshore. Once on the foreshore the sediment would come under the influence of waves acting on the beach and could, therefore, become effectively lost to the circulation around the sandbank. The foreshore immediately south of the Skegness Middle could, therefore, become subject to net receipt of sediment from the nearshore zone. Further evidence of this process and the implications for beach development will be discussed in later Chapters.

The Inner Dogs Head, an ebb-tidal delta, also probably represents a more or less closed circulation of sediment. South of the flood shield the western side of the sandbank is dominated by ebb tidal currents in the Boston Deep whereas the eastern side is dominated by flood tidal currents in the Parlour Channel. A circulation, therefore probably occurs around the southern part of the sandbank which is being added to by the sediment transported south on both sides of the sandbank by flood tidal currents north of the flood shield.

This hypothetical circulation of sediment around the southern 2/3 of the Inner Dogs Head would require a transfer of material in a west to east direction across the sandbank in the area of the flood shield. Such a movement appears possible on the basis of bedform orientations north of the flood shield. The bedforms on the western side of the sandbank north of the flood shield have orientations which show a much stronger tendency for sediment migration towards the central section of the flood shield than bedforms on the eastern side of the sandbank. This difference of bedform orientations on either side of the long axis of the sandbank could be a reflection of the tendency for a west to east drift of sediment across the sandbank at the location of the flood shield.

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CHAPTER NINE

WOODHEAD SEABED DRIFTER EXPERIMENTS

The various items of evidence of sediment movement from the studies in Chapters 3 to 7, integrated to construct the descriptive sediment movement model, were essentially collected at a point in either time or space. The Woodhead seabed drifter, on the other hand, is a freemoving object which, having a slight negative buoyancy, moves over the seabed at a velocity as close as possible to that of the water and will, therefore, after release at a selected site into a water circulation system and subsequent stranding and recovery on a coastline provide evidence of residual tidal currents through both time and space.

The Woodhead seabed drifter was designed to a standard specification and tested by Woodhead and Lee (1960). The drifters used in the present study conform to this specification and consist of a polythene saucer, 19 cm. in diameter. Punched into the saucer are four equidistant holes of 2 cm. diameter at a distance of 3 cm. from the centre. The holes, which have an empirically determined optimum size, avoid the development of both back pressure and air pockets behind the saucer which could deflect water flow and reduce the speed of movement of the drifter relative to the water. The saucer is coloured red for ease of location after stranding on a coastline.

Stability for the saucer is provided by a 54 cm. long solid flexible polyvinyl tail which is attached to the centre of the saucer. The saucer and tail together have a positive buoyancy of 3.8 gms. which is overcome by a copper weight, which also creates a slight negative buoyancy, attached 6 cm. from the free end of the tail. Woodhead and Lee (1960) suggested an optimum weight of

7 gms. for use of the drifters in seawater.

A speed calibration by D.J. Ellett (reported in Phillips (1970)) over distances between 2.5 and 5 m. in a flume suggested a relationship between water speed and drifter speed of the form :-

$$y = 1.099x + 3.9$$

where y = water speed

and x = drifter speed

According to this calibration the response of the drifter to water flow varies between 70% at a water speed of 20 cm./sec. and 90% at a speed of 103 cm./sec. At water speeds less than 20 cm./sec. the drifter is not very sensitive to water movement.

The collection and recording of the location of the stranded drifters relies upon the general public. Instructions for the finder were contained on a waterproof plastic post card which was attached to the drifter by means of heavy duty nylon fishing line. The post card was tied as tightly as possible to the drifter saucer to avoid the possibility of snagging on submerged objects or marine vegetation. The post card contained the following information :-

1. A return address
2. The following instructions :-

REWARD

THIS IS PART OF A RESEARCH PROJECT. PLEASE COMPLY WITH THE INSTRUCTIONS BELOW AND RETURN TO ADDRESS OPPOSITE, FOR A REWARD.

PLEASE MARK "X" ON THE MAP OR INSET OVERLEAF TO SHOW WHERE THE

CARD WAS FOUND. ALSO STATE DATE OF FIND.

IF THE CARD WAS FOUND BEYOND THE AREA SHOWN IN THE INSET GIVE NAME OF NEAREST VILLAGE OR TOWN.

SENDERS NAME AND ADDRESS (TO WHICH THE REWARD WILL BE SENT).

THANKYOU VERY MUCH FOR YOUR HELP.

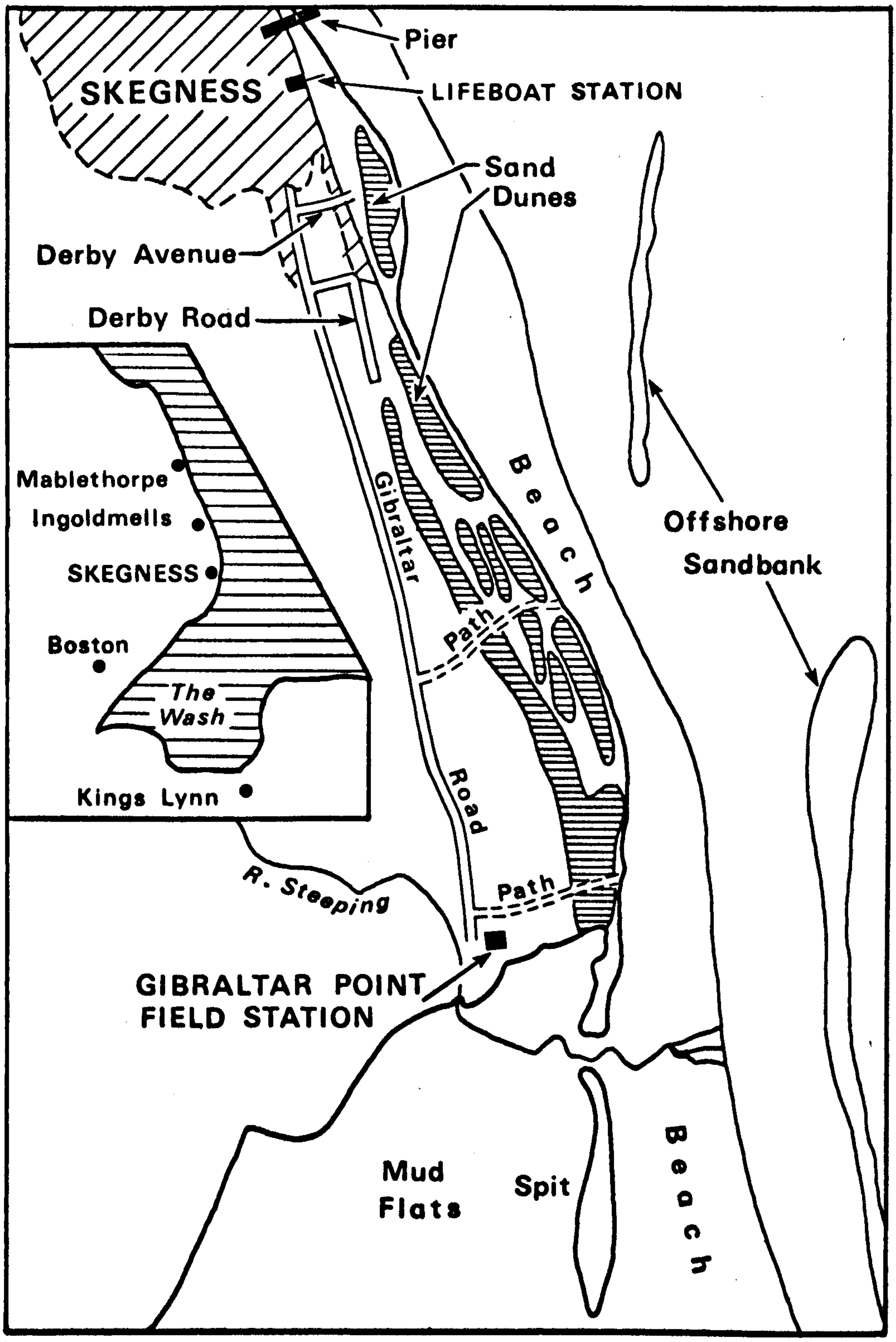
----

3. A map, which is reproduced as Figure (52A). The major criterion for map design was ease of location at any point on the map even by a casual visitor to the anticipated recovery area. Points of access to the coastline and prominent features on the coastline were emphasised.

The reward paid to the finder was £0.25, an amount set by international agreement. (Phillips, 1970).

A total of 6 releases of 50 drifters each were made, 3 in late March and 3 in late October 1973. A boat was located using compass bearings and anchored as near as possible to the selected sites for drifter releases. Drifters belonging to each release were marked, for later recognition, with a system of holes punched in the plastic post cards. Drifters were introduced into the sea individually, making sure no air pockets were present under the drifter saucers. Drifters are commonly released tied in bundles with soluble string which dissolves 20 to 30 minutes later when the bundles are lying on the seabed. Since all releases in the study area were made in

FIGURE 52A



Pier
SKEGNESS
LIFEBOAT STATION
Sand Dunes
Derby Avenue
Derby Road
Mablethorpe
Ingoldmells
SKEGNESS
Boston
The Wash
Kings Lynn
Gibraltar
Road
Path
Path
Beach
Offshore Sandbank
R. Steeping
GIBRALTAR POINT FIELD STATION
Mud Flats
Spit
Beach

relatively shallow water and sinking rate of drifters was quite rapid a sophisticated release mechanism was not considered necessary. Also the method of attaching the post cards to the drifters commonly resulted in tangling which could have persisted after drifters in bundles were released into the sea. A minimum of two people were employed in releasing drifters,a release of 50 being made in less than 100 seconds.

The locations of the release points are shown in Figure 52 The release of 26th March was made 2 hours after low water, that of 28th March 1 hour before high water and that of 29th March 1 hour after high water. All these releases were made under neap tide conditions. The release of 23rd October was made 2 hours before high-water and 3 days before the spring tides of October 26th. The releases of 28th October and 29th October were made 2 hours before high water and 2 days after spring tide conditions.

The releases of late March were made in and around the sandbank system south of Skegness to assess the nature and extent of the net tidal residuals in the area. These intial releases suggested a net northerly tidal residual extending as far north as Ingoldmells Point. The reasons for the choice of locations of the releases of late October were two fold. Firstly, two more releases were made within the sandbank system to compliment and assess the reliability of the initial releases. Secondly, a release was made approximately 2 km. offshore from Ingoldmells Point to substantiate the existance and extent of the net northerly tidal residuals in the area.

Before assessing the influence of environmental parameters on drifter movement, particularly the relative importance of wind and tidal currents, it was necessary to establish the possibility of bias being introduced by the efficacy and accuracy of the general public in recording the location and time of recovery of the drifters. To this end bogus releases were made similar to those described by Riley and Ramster (1972). Fifty drifters were serially numbered, half being placed on the beach during the months of May, June and July and half during the months of October, November and December, their location and number recorded. Drifters were deployed at dusk and at periods when the tide was tending towards neap conditions. This expedient ensured that drifters were beyond the reach of waves for a period of at least one week and could not be found until the following day. Movement by wind was also eliminated by burying the tail and part of the saucer of the drifter in the beach.

Table 11 shows the recovery rate and recovery time of the bogus release drifters in both the summer and winter periods. Of the summer bogus release 76% of the drifters were returned and of these 79% were recovered within 1 day of release. During the winter period a slightly higher number, 86%, of the drifters were returned and of these 68% were recovered within 1 day of release.

The history of the drifter returned 60 days after emplacement during the summer period is not known. One possible explanation is that it was recovered from the beach, only to be dropped in the marsh, where it remained until second recovery some 60 days later. This spurious occurrence is not considered significant in terms of the conclusions which follow.

Of a total recovery of 80% of the drifters placed on the beach 80% were returned within 1 day of release, 90% within 2 days and 95% within 3 days. On the basis of this evidence it is reasonable to

TABLE 11

BOGUS RELEASES.

SUMMER PERIOD		WINTER PERIOD	
Recovery time after release (days).	Number recovered.	Recovery time after release (days).	Number recovered.
1	15	1	17
2	1	2	3
3	2	3	0
60	1	4	1
Total recovered	19	Total recovered	21

Number of drifters released : 50

Total recovery rate : 80%

assume, for the purposes of the following analyses of true releases, that drifters were recovered on the day of stranding on the beach.

The total recovery rate of 80% for the bogus releases, compared with 70% for the true releases, suggests that a further 52 drifters (17%) of the true releases may have reached the beach but were not returned and 39 drifters (13%) may have been wasted at sea.

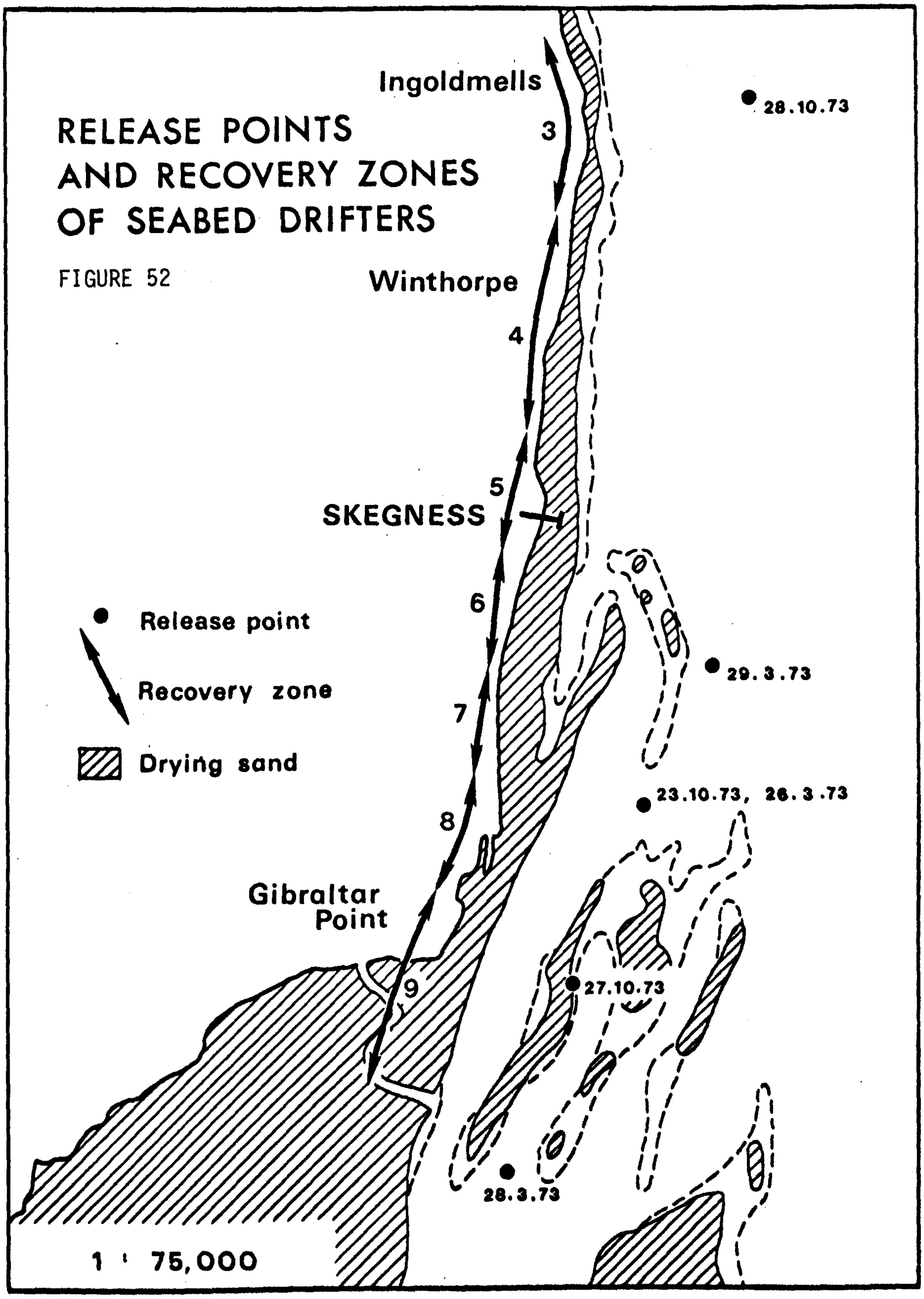
The general publics accuracy of estimating the location of drifters stranded on the beach can also be assessed in terms of the bogus release. For both bogus and true releases drifter locations were assigned to zones of the beach rather than point locations. A pilot release prior to intiation of true releases suggested a large concentration of drifters could be expected in the area between Skegness Pier and Gibraltar Point. Also, the general public needed specific landmarks to accurately locate their position on the beach. Consequently, recovery zones were established with landmarks (e.g. Skegness Pier) or points of access to the beach (e.g. the path at Gibraltar Point) centrally located. In areas where high concentrations of drifters were expected relatively short sections of coast were assigned to zones to adequately divide the drifter return distribution. Figure 52 and Table 12.

Table 13 shows the actual zones in which the serially numbered drifters were placed and the locations, assigned to zones, estimated by the finder. In the summer period 74% and in the winter 76%, of the drifters returned were correctly located. A further 26% of returns in the summer period and 19% in the winter period, were located in adjacent zones. A total of 98% of drifters located by the general public in either correct or adjacent zones

TABLE 12

RECOVERY ZONES

1. Mabelthorpe
2. Chapel St. Leonards
3. Ingoldmells
4. Winthorpe
5. Skegness Pier
6. Derby Avenue
7. Skegness Middle
8. Gibraltar Point Path
9. Gibraltar Point Spit
10. Wainfleet to Boston
11. East side of the Wash



RELEASE POINTS
AND RECOVERY ZONES
OF SEABED DRIFTERS
FIGURE 52
Ingoldmells
Winthorpe
SKEGNESS
Gibraltar Point
3
4
5
6
7
8
9
28.10.73
29.3.73
23.10.73, 26.3.73
27.10.73
28.3.73
Release point
Recovery zone
Drying sand
1 : 75,000

TABLE 13

Actual and estimated locations of drifters returned from the bogus releases.

SUMMER PERIOD			WINTER PERIOD		
Drifter Number	Location Zones		Drifter Number	Location Zones	
	Actual	Estimated		Actual	Estimated
1	9	-	26	9	8
2	9	9	27	9	8
3	8	-	28	9	9
4	8	8	29	8	8
5	7	-	30	8	8
6	7	7	31	8	8
7	7	6	32	7	-
8	6	5	33	7	-
9	6	6	34	7	7
10	5	5	35	6	7
11	5	5	36	6	8
12	5	4	37	6	6
13	4	4	38	5	5
14	4	4	39	5	5
15	2	2	40	5	5
16	2	-	41	4	5
17	1	1	42	4	5
18	1	1	43	4	4
19	10	-	44	3	3
20	10	10	45	3	3
21	9	10	46	2	2
22	8	-	47	2	2
23	7	7	48	10	10
24	8	8	49	10	-
25	9	8	50	10	-

in terms of the bogus release, suggests that estimated drifter locations can be taken as valid for the purpose of analysis of true drifter releases.

Having established that day of recovery and day of stranding, and estimated location and true location of drifters are essentially the same, information regarding true releases can be analysed without the application of correction factors.

The data of drifter returns were analysed for bias due to either of the environmental parameters of wind and tidal currents effecting the movement and subsequent stranding of drifters on the beach. Dominance of either wind or tidal currents as causitive agents in drifter movement would indicate which, if any, of the two factors could be reponsible for sediment movement, particularly in terms of the net sediment budget, between the nearshore and foreshore zones.

Also, the distribution of stranded drifters along the coast was analysed to detect preferred locations of drifter recovery. Any preference could be indicative of areas of net residual current and sediment movement from the nearshore to the foreshore zones.

BIAS TOWARDS ENVIRONMENTAL PARAMETERS

Several previous studies employing seabed drifters have found bias towards both environmental parameters and days of the week. Perkins, Williams and Bailey (1964) found bias towards return of drifters at times of spring tides as compared with neap tides and a secondary bias towards returns at weekends relative to other days of the week. Harvey (1968) found bias towards returns on Sunday. Phillips (1968, 1969), on the other hand, found little bias towards tidal conditions or days of the week but noted increased returns during periods with strong offshore winds. Riley and Ramster (1972) found pronounced bias towards periods with strong offshore winds and spring tides. The latter relationship, however, was not considered valid since the returns were also associated with strong offshore winds which occurred shortly after release. Returns were found to be free of bias towards weekend periods but had an inexplicable bias towards the early part of the working week.

Since 91% of drifters in the present study were recovered within 30 days of the time of release, this period is employed as a suitable time scale for subsequent analysis.

Bias of drifter returns towards days of the week has proved a difficult phenomenon to explain but must be assessed before considering bias towards either wind or tidal currents. Table 14 shows drifter recoveries by days of the week for each of the six releases. A Chi- squared test was conducted with a null hypothesis that there was no significant difference between days of the week as regards a preferential frequency of drifter returns. A value of χ^2 = 12.86 was obtained with 6 degrees of freedom. The null hypothesis must, therefore be accepted. In other words the distribution of drifter returns on days of the week could occur by chance and there is no statistical preference to particular days. Fridays, however, with a total of 16 recoveries had consistently low values. A similar, inexplicable, relationship was found by Riley and Ramster (1972). Since this bias is not statistically significant it will be ignored when considering bias towards tidal currents and winds.

Riley and Ramster (1972) assessed preference for drifter returns

TABLE 14

DRIFTER RECOVERIES BY DAYS OF THE WEEK

	26.3.73	28.3.73	29.3.73	23.10.73	27.10.73	28.10.73	TOTAL RECOVERY PER DAY
MONDAY	8	13	5	3	4	2	35
TUESDAY	3	7	2	4	8	2	26
WEDNESDAY	1	0	3	9	17	5	35
THURSDAY	1	1	7	4	2	7	22
FRIDAY	1	0	5	3	2	5	16
SATURDAY	3	0	6	6	2	9	26
SUNDAY	4	14	2	1	7	2	30
RECOVERY PER RELEASE	21	35	30	30	42	32	190

associated with tidal conditions during the spring-neap tidal cycle. The assessment was based on the assumptions that, firstly during periods immediately after spring tide conditions drifters would be stranded for longer periods and therefore more likely to be recovered and, secondly, that during periods of stronger tidal currents associated with spring tides drifter, and sediment, movement would be greater than at neap tides and would therefore be more likely to move into the foreshore zone and become stranded. For the purpose of the present analysis tidal height at highwater, as predicted in Admiralty tide tables, was taken as indicative of tidal current strength during the spring-neap tidal cycle.

During the periods under consideration tidal height at highwater ranged between 6.37 meters at the highest spring tide and 4.0 meters at the lowest neap tide. The tidal height on each of 30 days after release of each batch of drifters was assigned to 10 equal categories of 0.25 meters each. The total number of drifters returned per day was computed for each category. (Table 15). The mean drifter return per day was 2.62. A Chi-squared test was conducted on the basis of the null hypothesis that there was no significant difference between tidal classes as regards a preferential frequency of total drifter returns. The test gave a χ^2 value of 48.455 with 9 degrees of freedom. In other words there is less than 0.1% probability that the null hypothesis is correct and the inverse of the null hypothesis, that is some preferential return of drifters as regards tidal height classes, must be accepted. A mean drifter return per day of 3.85 in the five highest tidal height classes compared with a mean of 1.38 for the five lowest class suggests a preference for drifter returns during periods

TABLE 15

Tidal height at highwater (meters)	4.01-4.25	4.26-4.50	4.51-4.75	4.76-5.00	5.01-5.25	5.26-5.50	5.51-5.75	5.76-6.00	6.01-6.25	6.25-6.50
Number of days in each category	2	5	6	4	7	4	8	16	11	3
Number of days on rising limb of tidal cycle	0	4	2	1	4	2	3	9	7	2
Number of days on falling limb of tidal cycle	2	1	4	3	3	2	5	7	4	1
Total drifters per day returns	0.5	0.2	1.66	1.25	3.29	5.25	2.0	3.13	4.55	4.33
Drifters per day return - rising limb	0	0	4.5	1.0	5.0	9.0	3.0	4.22	4.17	6.0
Drifters per day return - falling limb	0.5	1.0	0.25	1.33	1.0	1.5	1.4	1.71	4.25	1.0

with stronger tidal currents associated with spring tide conditions. The relationship, however, is not simple in that there is not a linear relationship between tidal height and drifter returns per day. Indeed, maximum returns occurred with tides with heights in the category immediately above the median, 5.26 - 5.50 meters.

The drifter returns per day were further subdivided into periods of rising and falling tides on the limbs of the spring-neap tidal cycle was 3.69 compared with 1.39 on the falling limb suggesting a preference for returns on the rising limb as the tides approach spring ride conditions. This finding is a contradiction of the assumption of Riley and Ramster (1972) that the chance of drifter recovery might be greater in periods after spring tides. The bogus releases also suggested that such an assumption may not be valid since drifters were recovered almost immediately after stranding and the chance of recovery would not be improved by stranding above the reach of future tides. It would appear, therefore, that drifter stranding is causally related to the increasing tidal current velocities as the tides approach spring tide conditions.

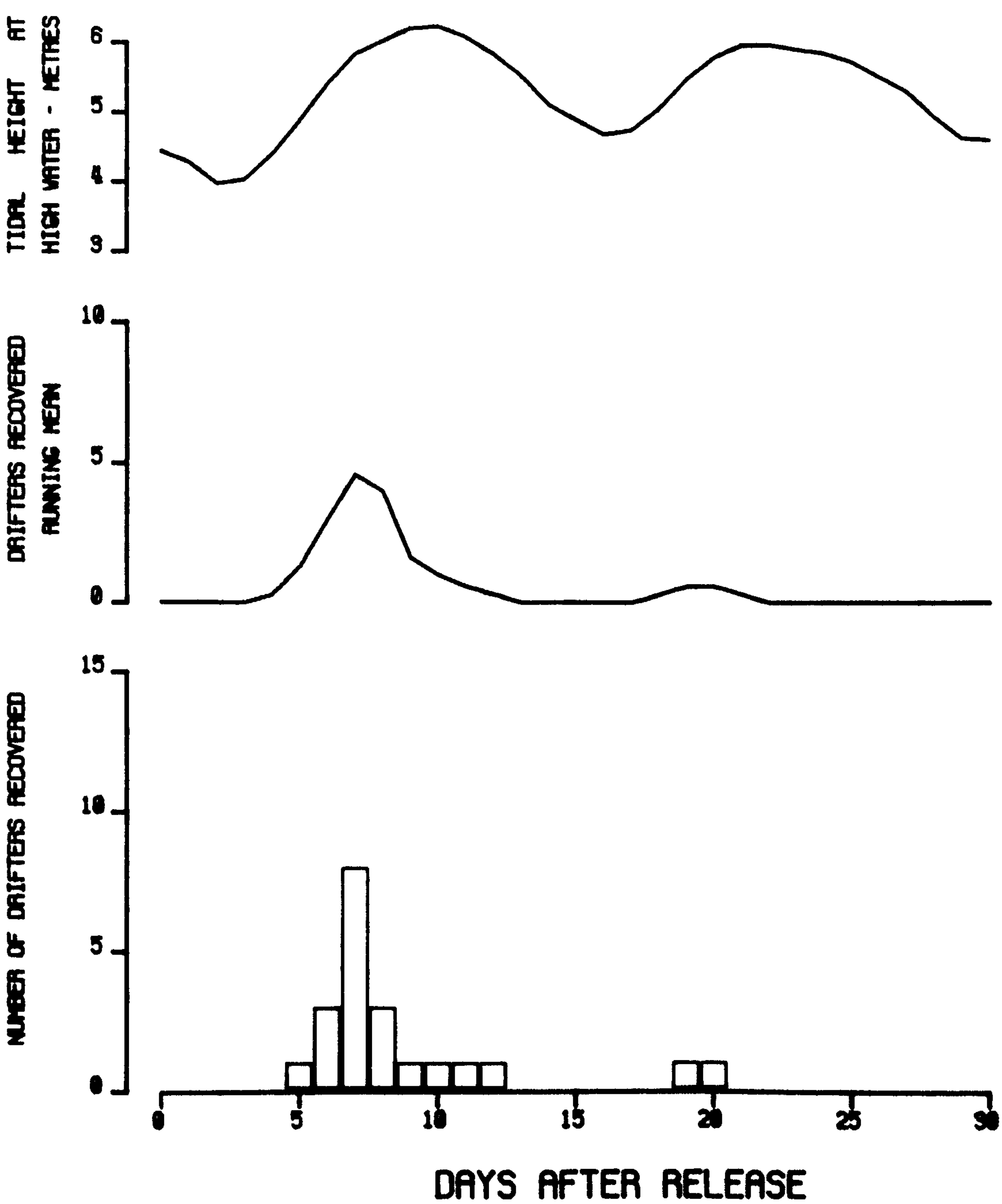
Chi-squared tests were conducted on the basis of the null hypothesis that there were no significant differences between tidal height classes as regards a preferential frequency of drifter returns on the rising limbs and falling limbs of the spring-neap tidal cycle. The tests gave χ^2 values of 34.77 and 38.51 repectively with 9 degrees of freedom in each case. Again the null hypothesis must be rejected and a preferential frequency of drifter returns must be accepted in both cases. On the rising limb the mean drifter returns per day for the five highest tidal categories was 5.28 compared with 2.1 for the five lowest categories. Corresponding figures for the falling limb were 1.97 and 0.82. In both cases, therefore, there is a tendancy for drifters to be stranded during periods when tidal currents are stronger.

The relationship between the spring-neap tidal cycle and drifter returns for each release are shown in Figures 53 to 58. The releases of March (Figures 53, 54 and 55) confirm the relationship discussed above but the picture presented by the releases of October (Figures 56, 57 and 58) is more complex. The differences in response of drifter returns to the spring-neap tidal cycle between the releases of March and October could be related to the time of release of the drifters relative to the tidal cycle. The releases of March were made during neap tide conditions and the majority of drifters were stranded on the rising limb of the following spring tides. The releases of October on the other hand were made during spring tide conditions and some drifters were stranded on the following falling limb of the tidal cycle. However, in all three releases of October the stranding rate increased on the subsequent rising limb. Although the patterns of drifter returns for the October releases are more dispersed they confirm, to a lesser extent, the relationship between drifter returns or strandings and the spring-neap cycle.

A seabed drifter investigation in Morecambe Bay (Phillips 1968, 1969) suggested variations in the rate of recovery of drifters was related to seabed drift of water compensating for surface movement produced by wind and also the degree of disturbance of the seabed by waves. Riley and Ramster (1972) noted an increase in drifter returns along a section of the Norfolk Coast at the times of southwesterly, offshore, gales which reflected a short term wind-water

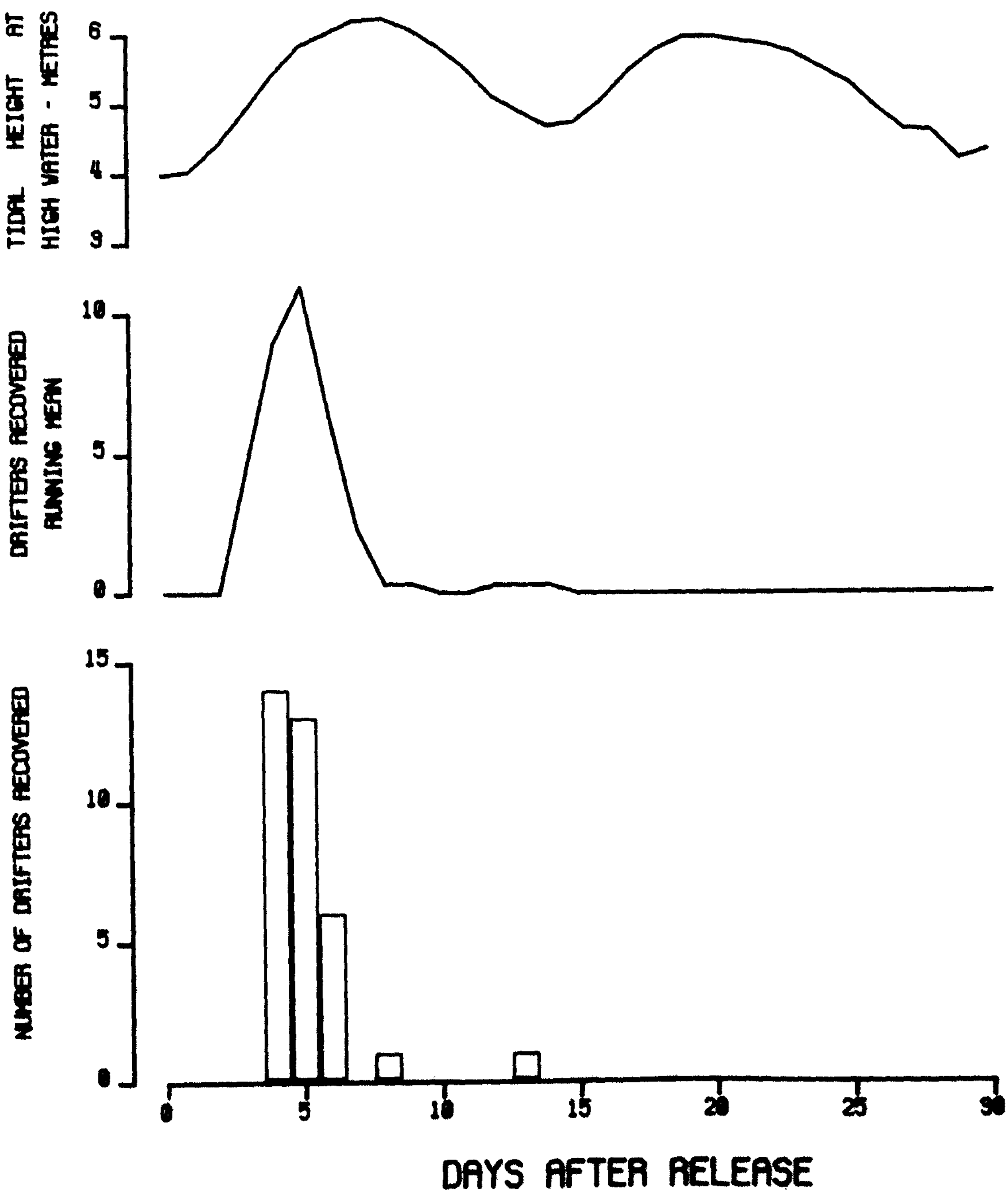
SEABED DRIFTERS : RELEASE DATE, 26.03.73

FIGURE 53



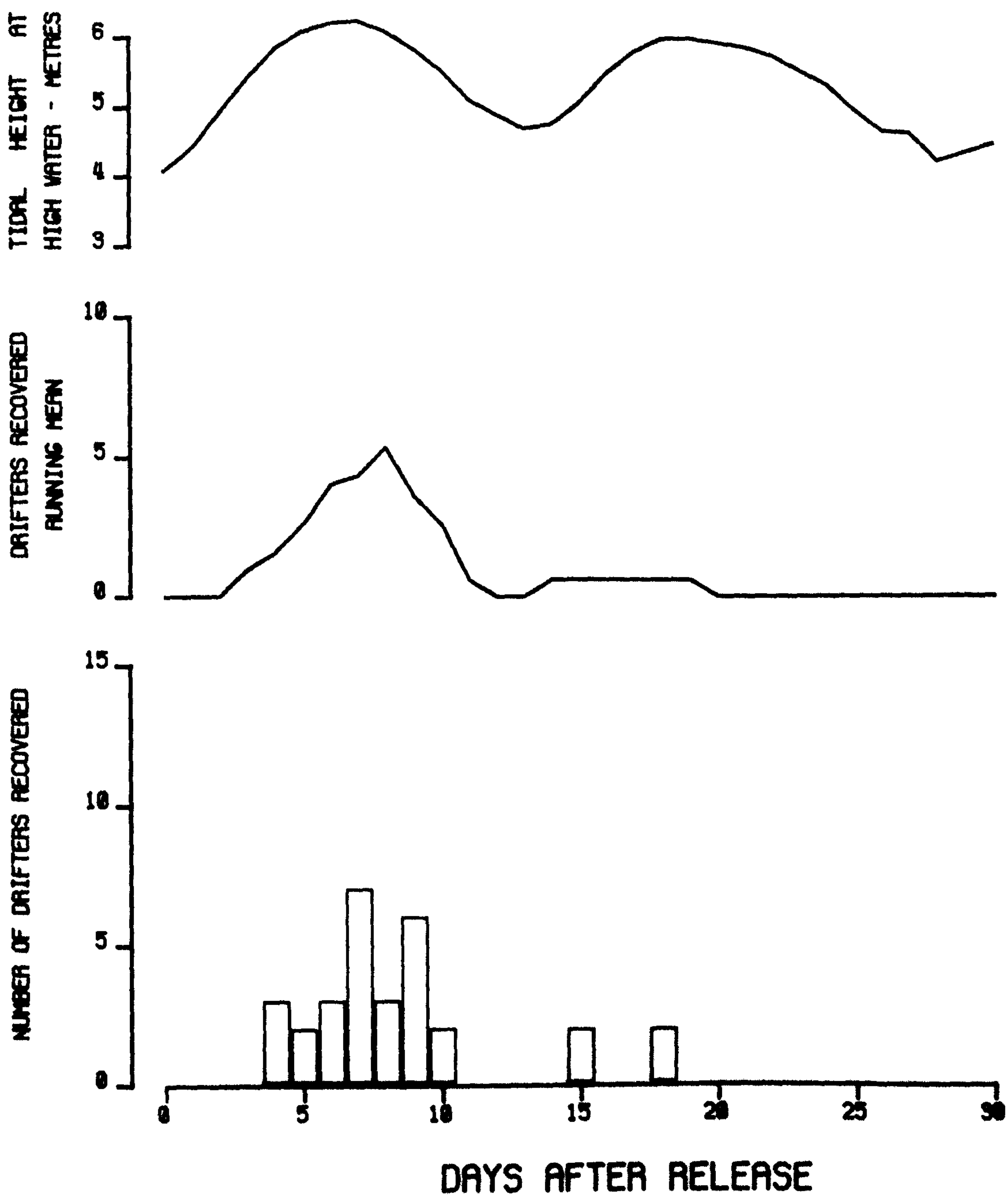
SEABED DRIFTERS : RELEASE DATE, 28.03.73

FIGURE 54



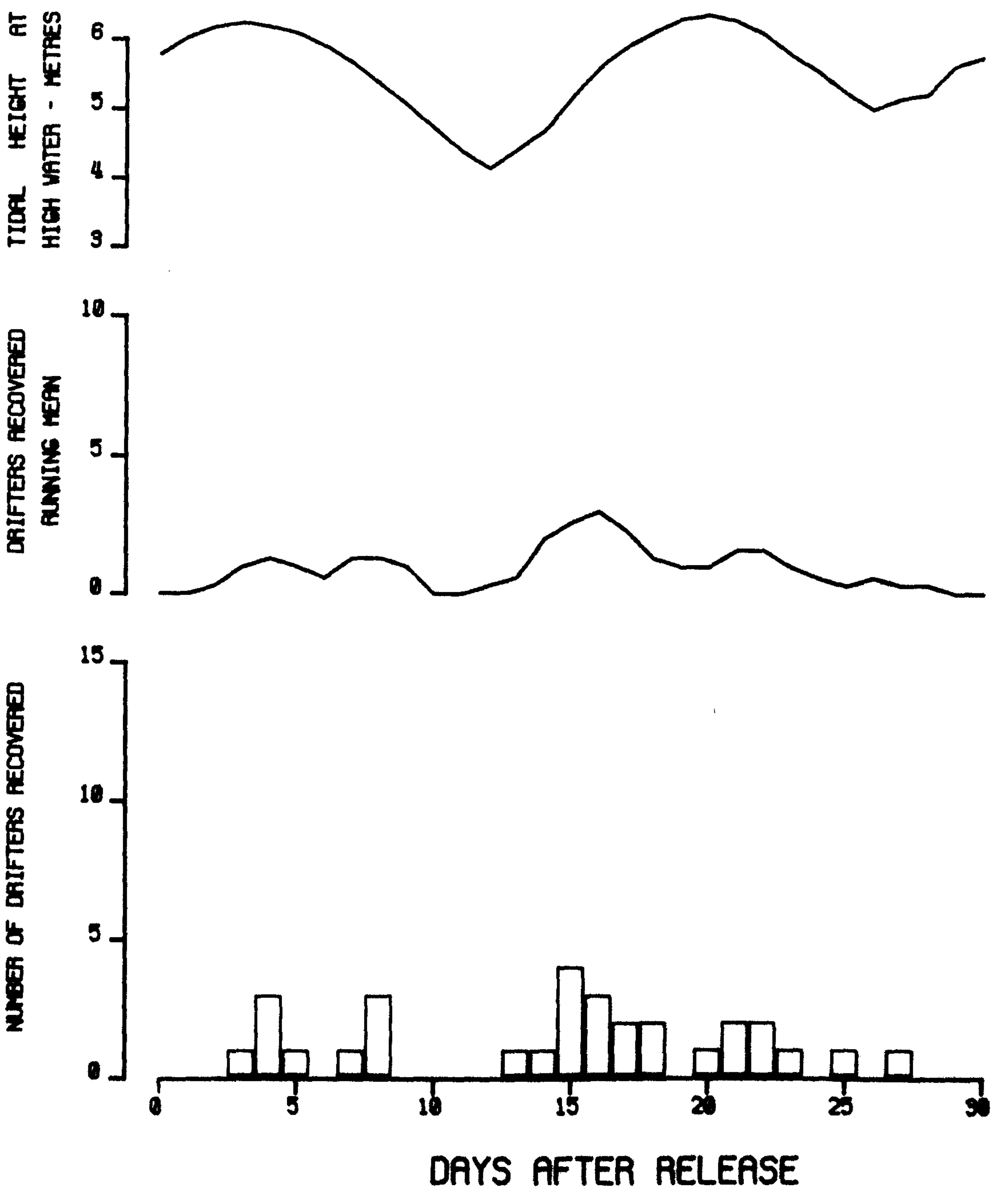
SEABED DRIFTERS : RELEASE DATE, 29.03.73

FIGURE 55



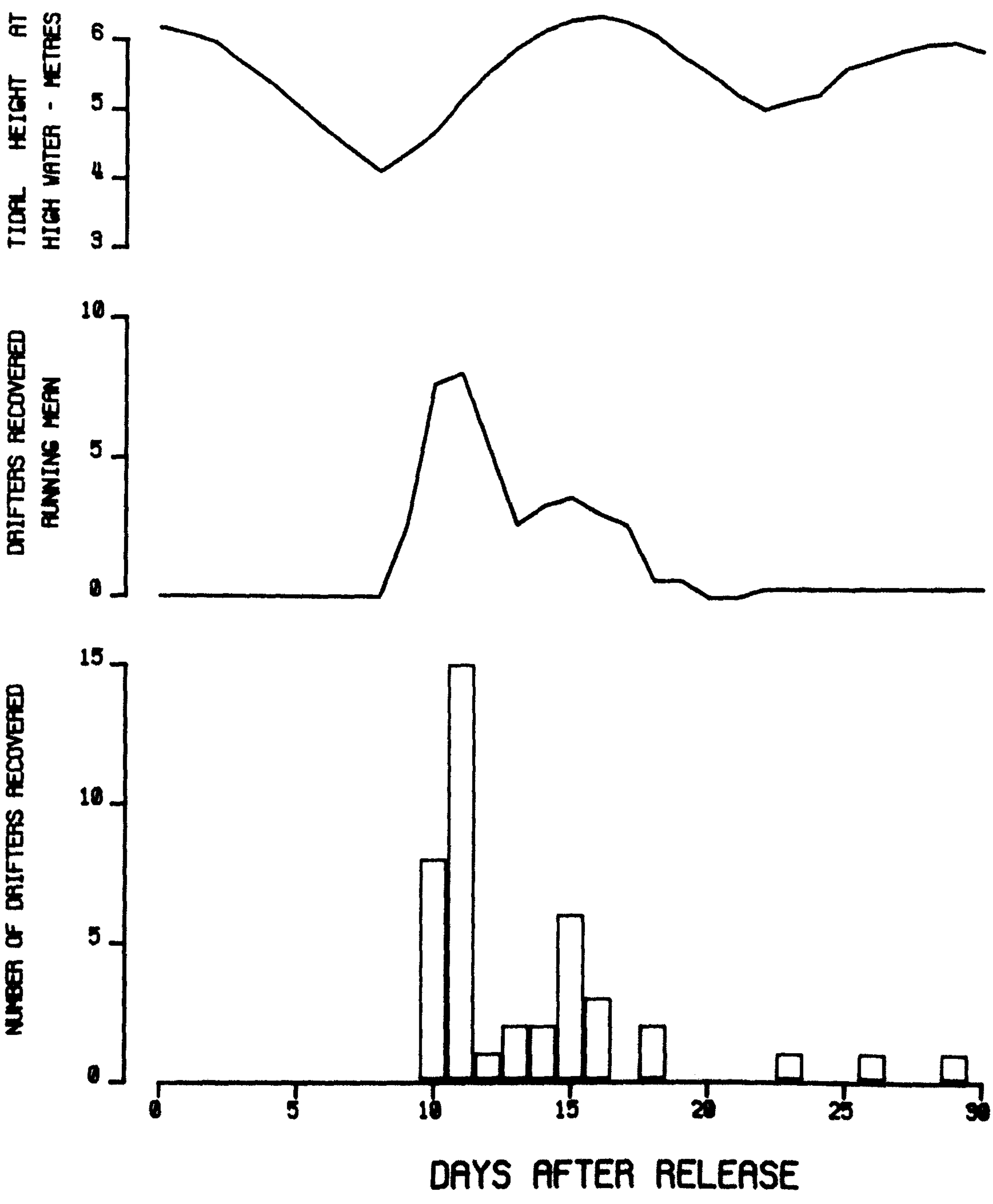
SEABED DRIFTERS : RELEASE DATE. 23.10.73

FIGURE 56



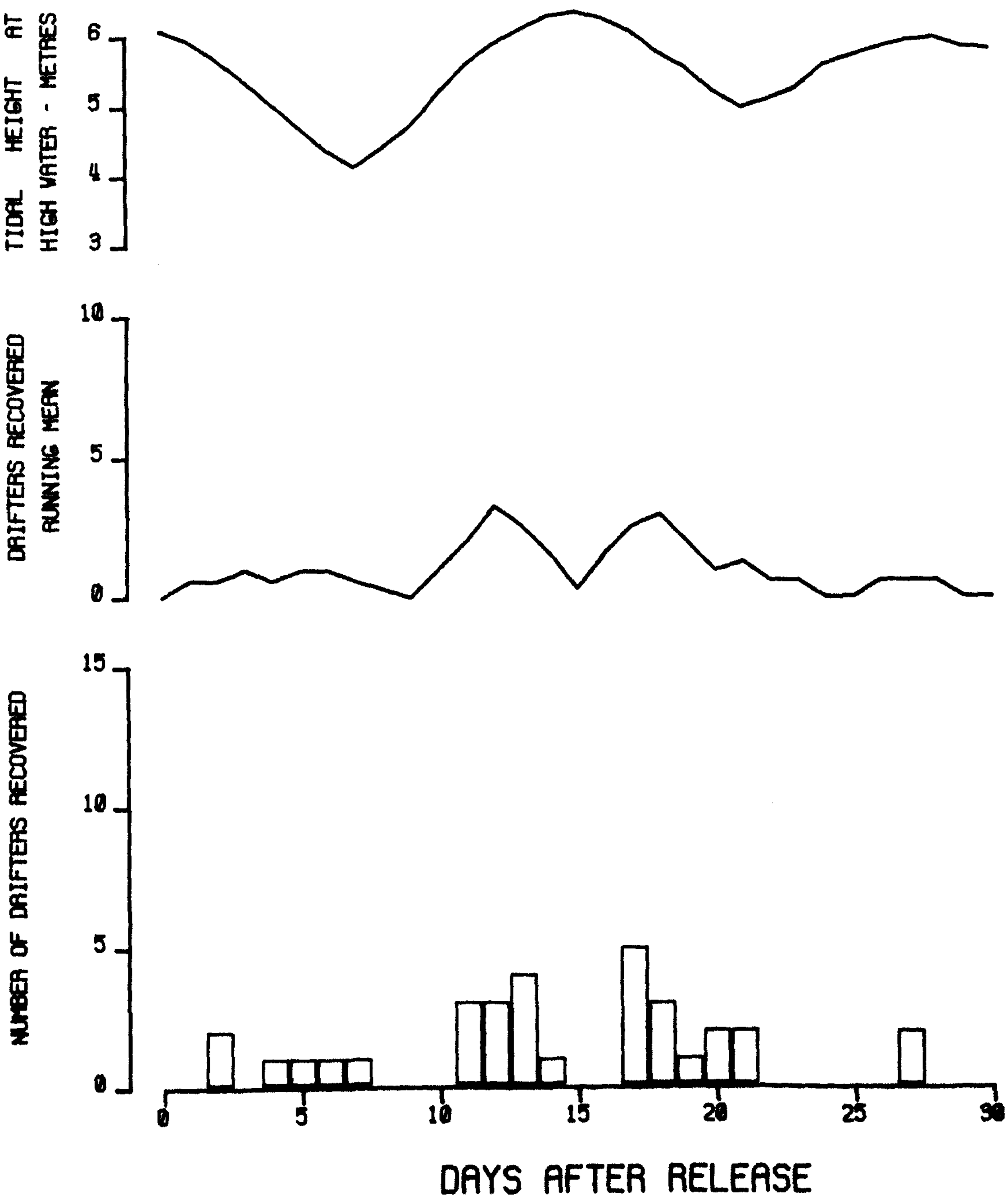
SEABED DRIFTERS : RELEASE DATE, 27.10.73

FIGURE 57



SEABED DRIFTERS : RELEASE DATE, 28.10.73

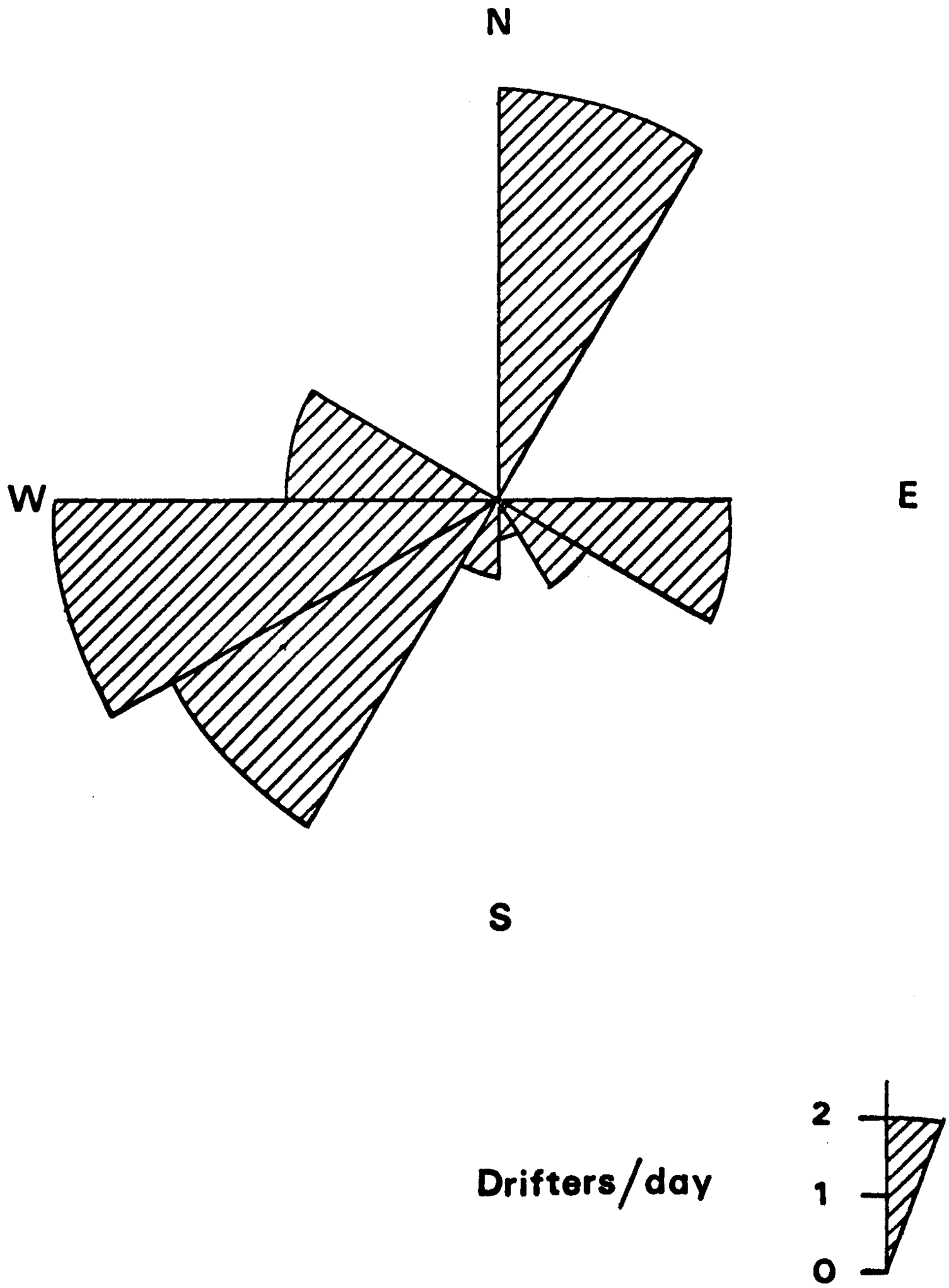
FIGURE 58



couple and not coastwise residual drift. Either critical depth or critical distance from the shore were thought to determine the nature of the response of the drifters to the wind-water couple but it was not possible to differentiate these two parameters due to lack of data. North-easterly and easterly gales did not increase drifter returns probably because the onshore surface water movement created by these gales would be countered by an offshore movement of water at depth.

The influence of wind speed and direction on the recovery rate of drifters was analysed for the releases of March and October. Wind direction during the 30 days after the release of each batch of drifters was divided into twelve 30 degree sectors. The number of drifters recovered per day in each wind sector for all releases was then calculated. A Chi-squared test was conducted on the basis of the null hypothesis that there was no significant difference between wind sectors as regards a preferential frequency of drifter returns. The test gave a χ^2 value of 109.65 with 11 degrees of freedom. There is less than 0.1% probability that the null hypothesis is correct and the inverse of the null hypothesis, that is a preferential return of drifters as regards wind sectors, must be accepted. Figure 59 shows drifter returns per day in each wind sector. Returns per day were greatest when the wind was blowing from a westerly to south-westerly direction, that is offshore. This finding is similar to that of Phillips (1968, 1969) and Riley and Ramster (1972) discussed above and probably reflects the wind-water couple described by these authors. An increased return of drifters when the wind was blowing from the north-northeast is con-

FIGURE 59 Vectors of drifters returned within wind sectors



trary to the finding of Riley and Ramster (1972) and cannot be explained in terms of the wind-water couple. However, north-north-east is the direction of maximum fetch and winds from this sector usually produce relatively large waves in the Skegness area. The suggestion of Phillips (1968) that the degree of disturbance of the seabed by waves could effect drifter returns may, therefore, be applicable to this finding.

Drifter returns per day in each wind sector were subdivided on the basis of wind strength or speed. No relationship between wind speed in any sector and drifter recovery rate could be found. It would appear, therefore, that wind direction is a more critical factor effecting drifter return rates, in the Skegness area, than wind speed.

It should be mentioned that a more reliable experiment to assess the influence of environmental parameters on drifter return rates could have been designed given greater availability of field-work time and resources. Ideally, drifters should have been released at a selected point at regular intervals over a considerable length of time. Such an experiment design would, given a sufficient time span, counteract irregularities in returns associated with time of release of drifters relative to the spring-neap tidal cycle and the chance occurrence of winds blowing from one sector in the period immediately after drifter release.

DRIFTER RECOVERY DISTRIBUTION

The location of recovery zone and the reasons for the choice of the zones have been discussed previously. For each of the six releases the distribution of the locations of the drifter strandings have be summarised in table form (Tables 16 to 21) in which the drifters have been assigned to recovery zones. For comparison of zones the returns have been reduced to the number of drifters per km. of the foreshore. Maps have been constructed with the actual locations of drifter strandings placed as accurately as possible on the basis of information supplied by the finder (Figures 60 to 65).

The distribution of drifter strandings will be described for each drifter release :-

1. The release of 26.3.73 (Table 16 and Figure 60). This release was made in the Wainfleet Road equidistant from the Skegness Middle and the Inner Knock. Of the 22 drifters recovered 19 reached the foreshore within 14 days of release. The largest concentration of drifter returns occurred in zone 7, the point where the Skegness Middle meets the foreshore. A density of 4.44 drifters per km. of foreshore was recorded at this location. Of the five drifters stranded south of this zone two took 19 and 20 days to reach the foreshore in zones 8 and 9 respectively.

2. The release of 28.3.73 (Table 17 and Figure 61). This was made in the Boston Deep between the Inner and Outer Knock sandbanks. Of the 38 drifters recovered 35 reached the foreshore within 14 days of release. Particularly large concentrations of drifters occurred at zones 5 and 7 with density of 6.67 and 8.15 drifters per km. respectively.

3. The release of 29.3.73 (Table 18 and Figure 62). This release was made offshore from the outer, eastern limb of the Skegness Middle. Of the 31 drifters recovered 26 reached the foreshore

TABLE 16

RECOVERY TIME OF DRIFTERS RELEASED ON 26.3.73

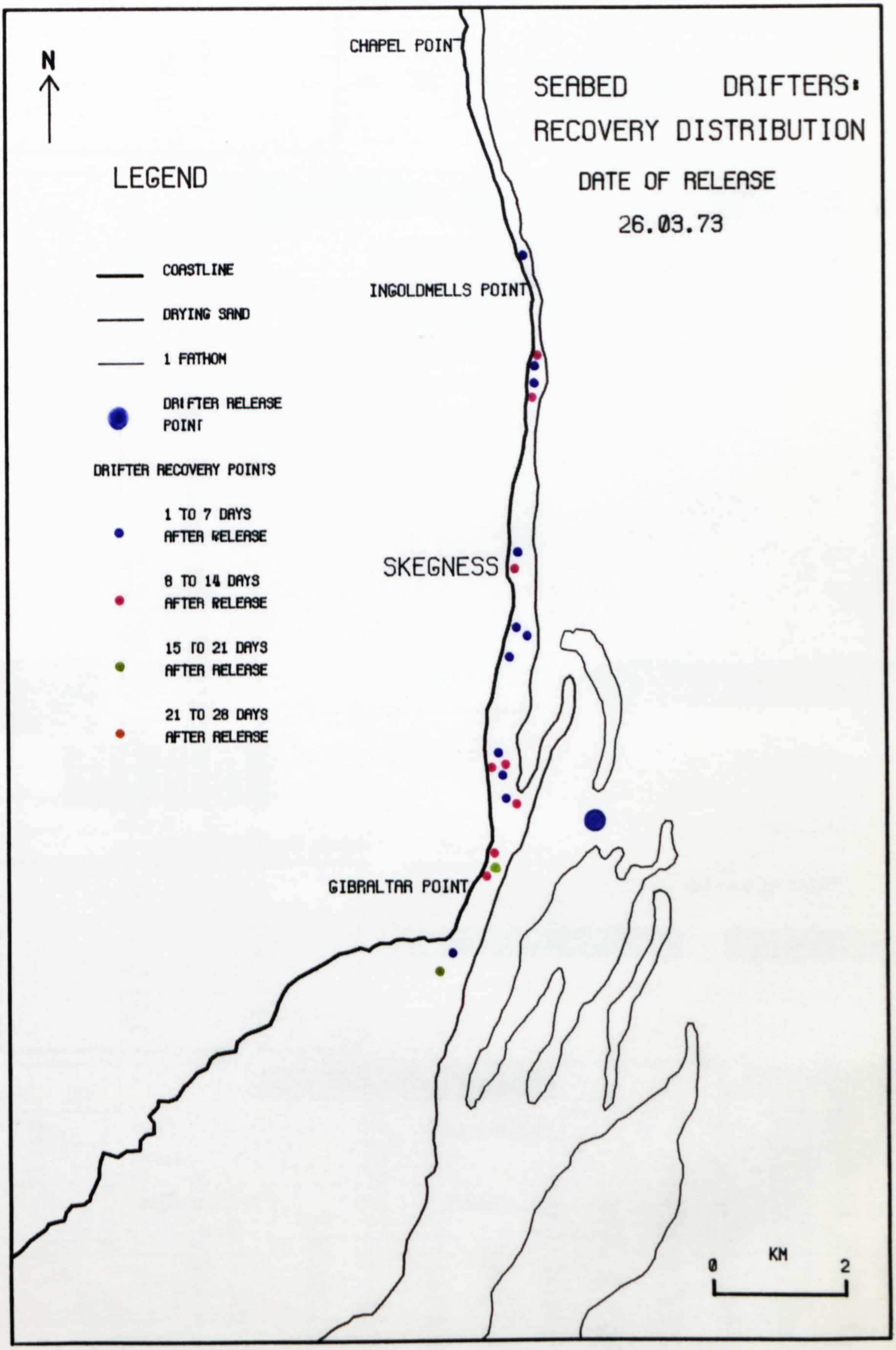
	RECOVERY TIME (DAYS)																															TOTAL	DENSITY
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AFTER 30	PER ZONE	DRIFTERS PER KM
MABELTHORPE																																0	0
CHAPEL ST.LEONARDS																																0	0
INGOLDMELLS							x																									1	.56
WINTHORPE							x x	x				x																				4	1.08
SKEGNESS PIER							x	x																								2	1.33
DERBY AVENUE					x		x x																									3	1.82
SKEGNESS MIDDLE						x x	x			x	x																					6	4.44
GIBRALTAR POINT PATH								x											x													3	2.07
GIBRALTAR POINT SPIT						x														x												2	.99
WAINFLEET TO BOSTON																															x	1	0
EAST SIDE OF WASH																																0	0

TOTAL RECOVERY 22

DRIFT TO NORTH

DRIFT TO SOUTH

FIGURE 60



N
CHAPEL POINT
SEABED DRIFTERS:
RECOVERY DISTRIBUTION
DATE OF RELEASE
26.03.73
LEGEND
COASTLINE
DRYING SAND
1 FATHOM
DRIFTER RELEASE POINT
DRIFTER RECOVERY POINTS
1 TO 7 DAYS AFTER RELEASE
8 TO 14 DAYS AFTER RELEASE
15 TO 21 DAYS AFTER RELEASE
21 TO 28 DAYS AFTER RELEASE
INGOLDMELLS POINT
SKEGNESS
GIBRALTAR POINT
0 KM 2

TABLE 17

RECOVERY TIME OF DRIFTERS RELEASED ON 28.3.73

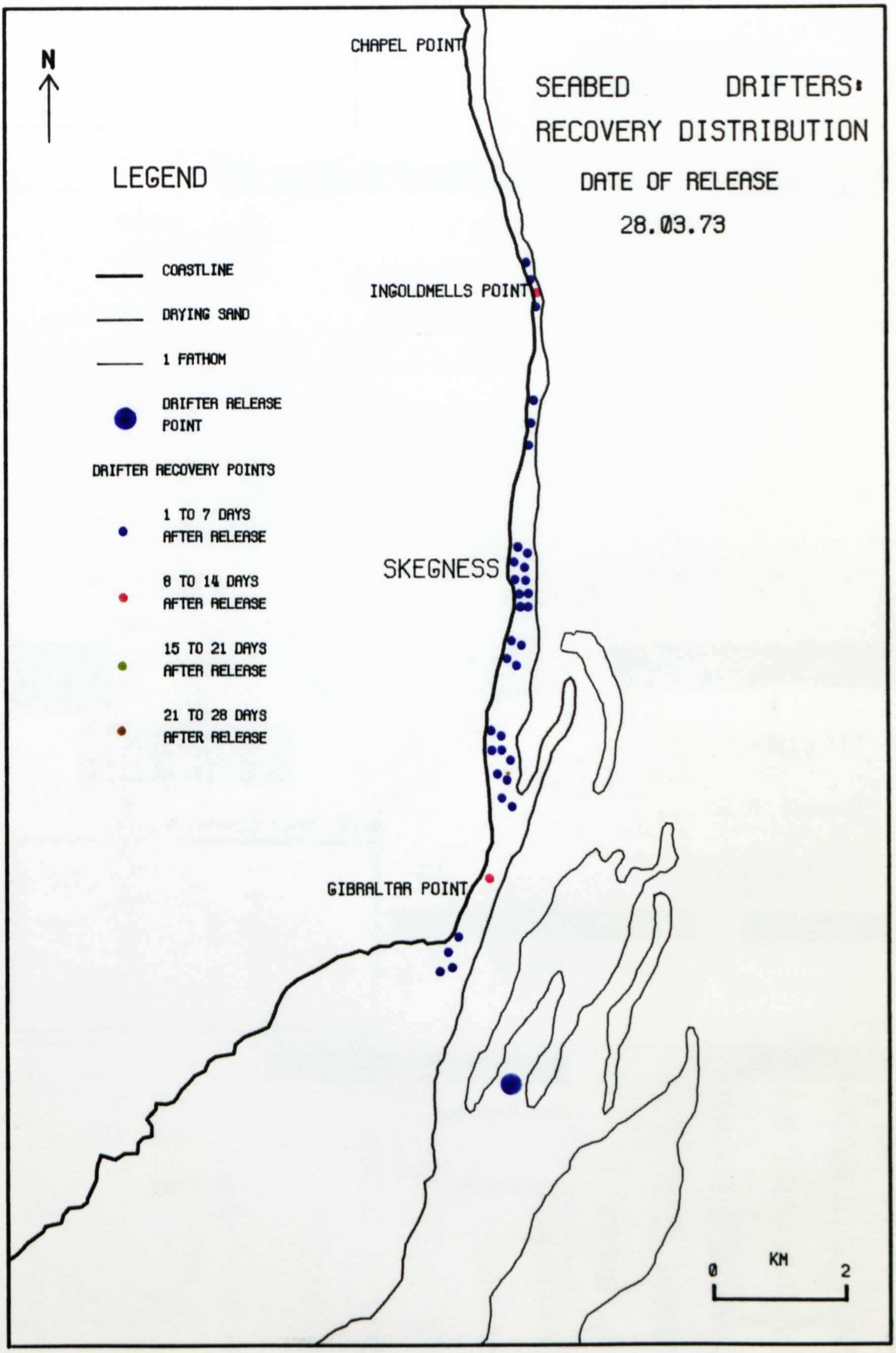
	RECOVERY TIME (DAYS) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AFTER 30	TOTAL PER ZONE	DENSITY DRIFTERS PER KM
MABELTHORPE																																0	0
CHAPEL ST.LEONARDS																																0	0
INGOLDMELLS					xx	x		x																								4	2.22
WINTHORPE					xx	x																										3	81
SKEGNESS PIER					xxxxxx	xxxx																										10	6.67
DERBY AVENUE				xxx	x																											4	2.42
SKEGNESS MIDDLE				xxxxxxx	xx																										xx	11	8.15
GIBRALTAR POINT PATH													x																		x	2	1.38
GIBRALTAR POINT SPIT				xxxx																												4	1.97
WAINFLEET TO BOSTON																																0	0
EAST SIDE OF WASH																																0	0

TOTAL RECOVERY 38

DRIFT TO NORTH

DRIFT TO SOUTH

FIGURE 61



N
CHAPEL POINT
SEABED DRIFTERS:
RECOVERY DISTRIBUTION
DATE OF RELEASE
28.03.73
LEGEND
COASTLINE
DRYING SAND
1 FATHOM
DRIFTER RELEASE POINT
DRIFTER RECOVERY POINTS
1 TO 7 DAYS AFTER RELEASE
8 TO 14 DAYS AFTER RELEASE
15 TO 21 DAYS AFTER RELEASE
21 TO 28 DAYS AFTER RELEASE
INGOLDMELLS POINT
SKEGNESS
GIBRALTAR POINT
0 KM 2

TABLE 18

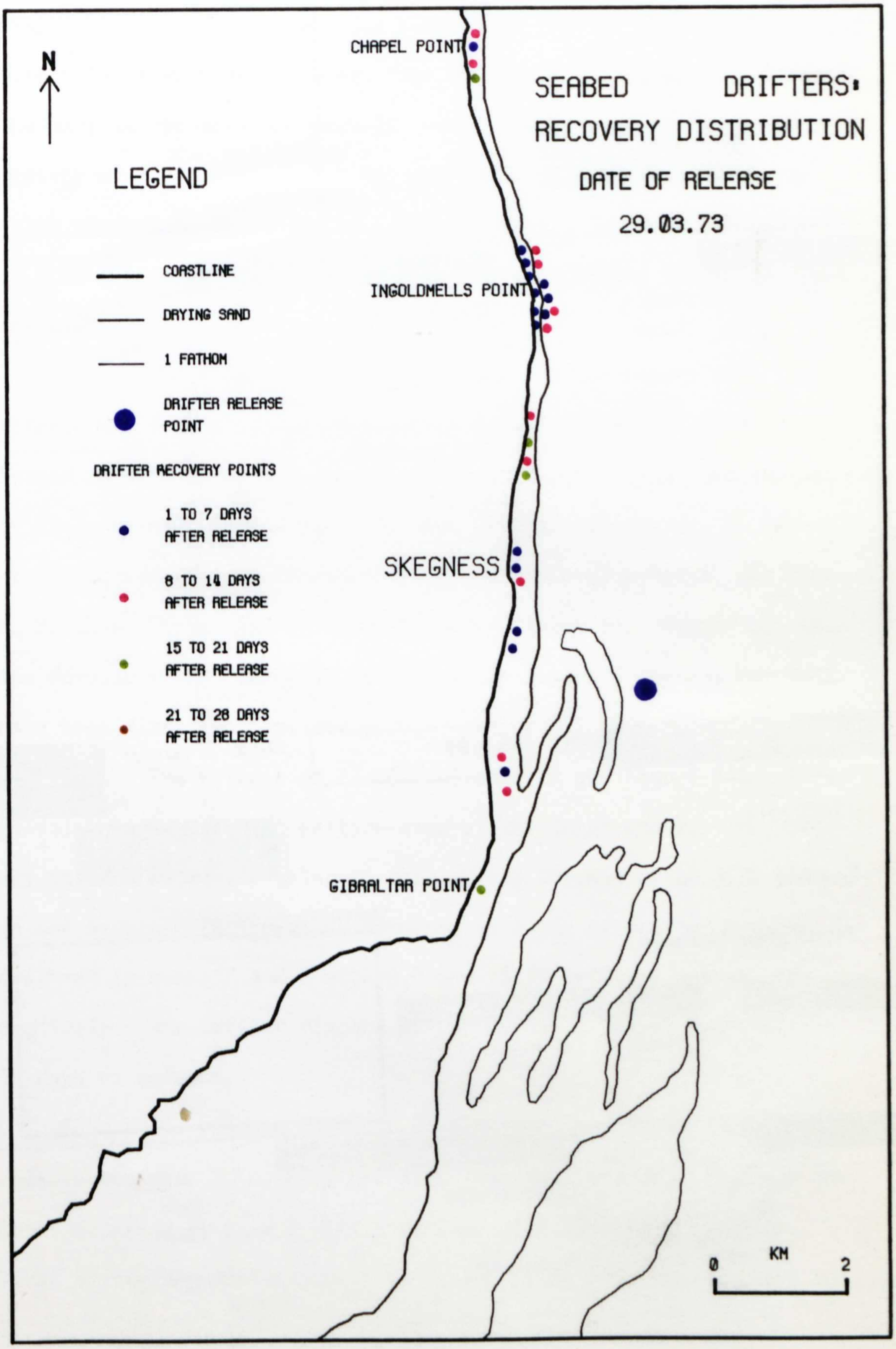
RECOVERY TIME OF DRIFTERS RELEASED ON 29.3.73

	RECOVERY TIME (DAYS) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AFTER 30	TOTAL PER ZONE	DENSITY DRIFTERS PER KM
MABELTHORPE																																0	0
CHAPEL ST.LEONARDS							x	x	x						x																	4	1.10
INGOLDMELLS				xx	xx		xxxxx	x	xx	x																						13	7.22
WINTHORPE								x	x									xx														4	1.08
SKEGNESS PIER				x		x				x																						3	1.82
DERBY AVENUE						xx																										2	1.21
SKEGNESS MIDDLE							x		xx																							3	2.22
GIBRALTAR POINT PATH															x																	1	.69
GIBRALTAR POINT SPIT																																0	0
WAINFLEET TO BOSTON																															x	1	0
EAST SIDE OF WASH																																0	0
																																TOTAL RECOVERY 31	

DRIFT TO NORTH

DRIFT TO SOUTH

FIGURE 62



N
LEGEND
COASTLINE
DRYING SAND
1 FATHOM
DRIFTER RELEASE POINT
DRIFTER RECOVERY POINTS
1 TO 7 DAYS AFTER RELEASE
8 TO 14 DAYS AFTER RELEASE
15 TO 21 DAYS AFTER RELEASE
21 TO 28 DAYS AFTER RELEASE
CHAPEL POINT
SEABED DRIFTERS:
RECOVERY DISTRIBUTION
DATE OF RELEASE
29.03.73
INGOLDMELLS POINT
SKEGNESS
GIBRALTAR POINT
0
KM
2

within 14 days of release. The pattern of drifter returns associated with this release is different from the releases discussed previously. The maximum recovery occurred at zone 3, Ingoldmells Point, with a density of 7.22 drifters per km. and four drifters reached as far north as zone 2, Chapel Point. However a relatively high density of 2.22 drifters per km. occurred at zone 7 as noted in the previous releases.

4. The release of 23.10.73 (Table 19 and Figure 63). This release was made at the same location as the release of 26.3.73. Rather surprisingly the recovery pattern is more comparable to that of 28.3.73 than that of 26.3.73. The maximum recoveries, in terms of drifter density, occurred at zone 3, Ingoldmells Point, and zone 5, Skegness Pier. All releases made in October took longer to reach the foreshore than those of March and the possible reasons for this have been discussed previously.

5. The release of 27.10.73 (Table 20 and Figure 64). This release was made on the eastern side of the Inner Knock. The recovery pattern is very similar to that of the release of 28.3.73 made in the Boston Deep. Maximum returns, in terms of drifter density, occurred in zones 7 and 8 with 9.7 and 10.37 drifters per km. respectively. One drifter reached as far north as Chapel Point within 15 days of release.

6. The release of 28.10.73 (Table 21 and Figure 65). This release was made 2 km. offshore from Ingoldmells Point. Maximum returns occurred at zone 3 with a density of 8.89 drifters per km. Three drifters travelled north to Chapel Point and three reached zone 7.

TABLE 19

RECOVERY TIME OF DRIFTERS RELEASED ON 23.10.73

RECOVERY TIME (DAYS)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AFTER 30	TOTAL PER ZONE	DENSITY DRIFTERS PER KM
MABELTHORPE																																0	0
CHAPEL ST.LEONARDS				x																			x		x							3	.82
INGOLDMELLS													x	x				x		x	x	xx									xxx	10	5.56
WINTHORPE				x												x	xx	x														5	1.35
SKEGNESS PIER				x			x	xxx							x	x																7	4.67
DERBY AVENUE			x												xx	x																4	2.42
SKEGNESS MIDDLE					x										x																	2	1.48
GIBRALTAR POINT PATH																					x						x					2	1.38
GIBRALTAR POINT SPIT																															xx	2	.99
WAINFLEET TO BOSTON																																0	0
EAST SIDE OF WASH																															x	1	0

TOTAL RECOVERY 36

DRIFT TO NORTH

DRIFT TO SOUTH

FIGURE 63

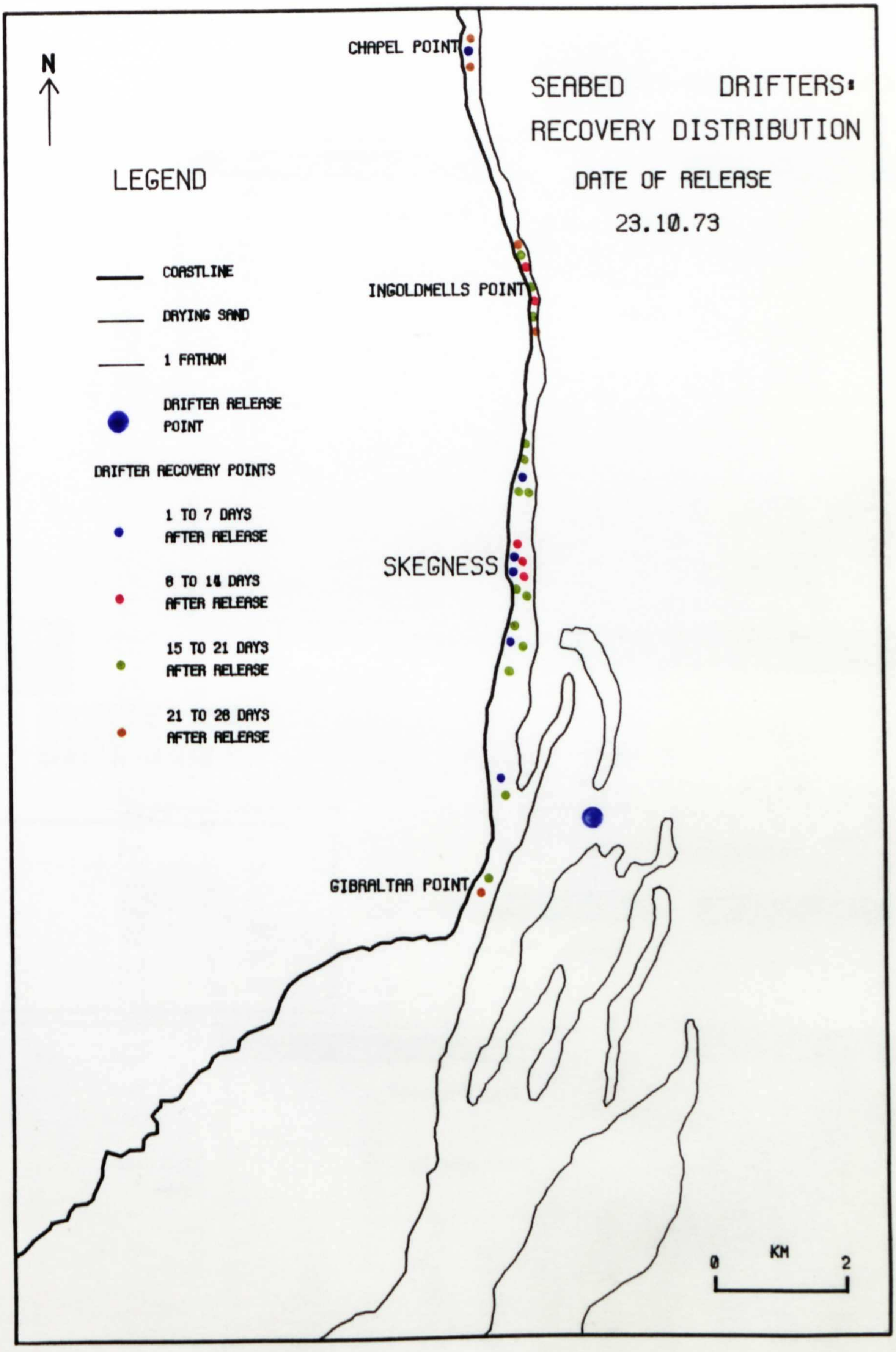

N
SEABED DRIFTERS:
RECOVERY DISTRIBUTION
DATE OF RELEASE
23.10.73
LEGEND
COASTLINE
DRYING SAND
1 FATHOM
DRIFTER RELEASE POINT
DRIFTER RECOVERY POINTS
1 TO 7 DAYS AFTER RELEASE
8 TO 14 DAYS AFTER RELEASE
15 TO 21 DAYS AFTER RELEASE
21 TO 28 DAYS AFTER RELEASE
CHAPEL POINT
INGOLDMELLS POINT
SKEGNESS
GIBRALTAR POINT
0 KM 2

TABLE 20

RECOVERY TIME OF DRIFTERS RELEASED ON 27.10.73

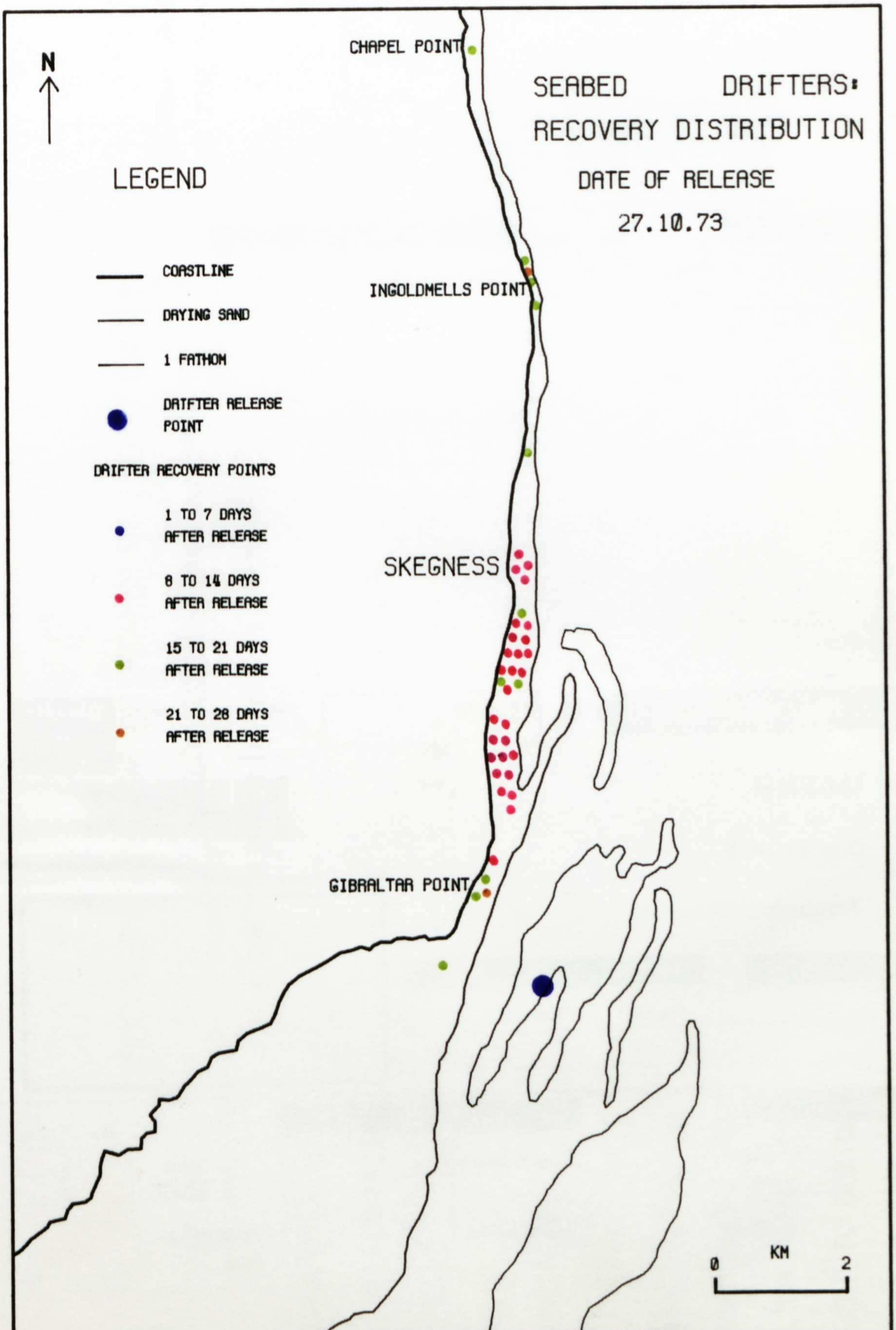
	RECOVERY TIME (DAYS)																															TOTAL	DENSITY
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AFTER 30	PER ZONE	DRIFTERS PER KM
MABELTHORPE																																0	0
CHAPEL ST.LEONARDS															x																	1	.27
INGOLDMELLS															x	x		x					x								x	5	2.78
WINTHORPE																		x														1	.27
SKEGNESS PIER										x			x	xx																		4	2.67
DERBY AVENUE										xxxxx	xxxxxx				xx	x															xx	16	9.70
SKEGNESS MIDDLE										xx	xxxxxxxxx		x																x		x	14	10.37
GIBRALTAR POINT PATH												x			x	x										x						4	2.76
GIBRALTAR POINT SPIT															x																	1	.49
WAINFLEET TO BOSTON																																0	0
EAST SIDE OF WASH																																0	0

TOTAL RECOVERY 46

DRIFT TO NORTH

DRIFT TO SOUTH

FIGURE 64



N
CHAPEL POINT
SEABED DRIFTERS:
RECOVERY DISTRIBUTION
DATE OF RELEASE
27.10.73
LEGEND
COASTLINE
DRYING SAND
1 FATHOM
DRIFTER RELEASE POINT
DRIFTER RECOVERY POINTS
1 TO 7 DAYS AFTER RELEASE
8 TO 14 DAYS AFTER RELEASE
15 TO 21 DAYS AFTER RELEASE
21 TO 28 DAYS AFTER RELEASE
INGOLDMELLS POINT
SKEGNESS
GIBRALTAR POINT
0
KM
2

RECOVERY TIME OF DRIFTERS RELEASED ON 28.10.73

TABLE 21

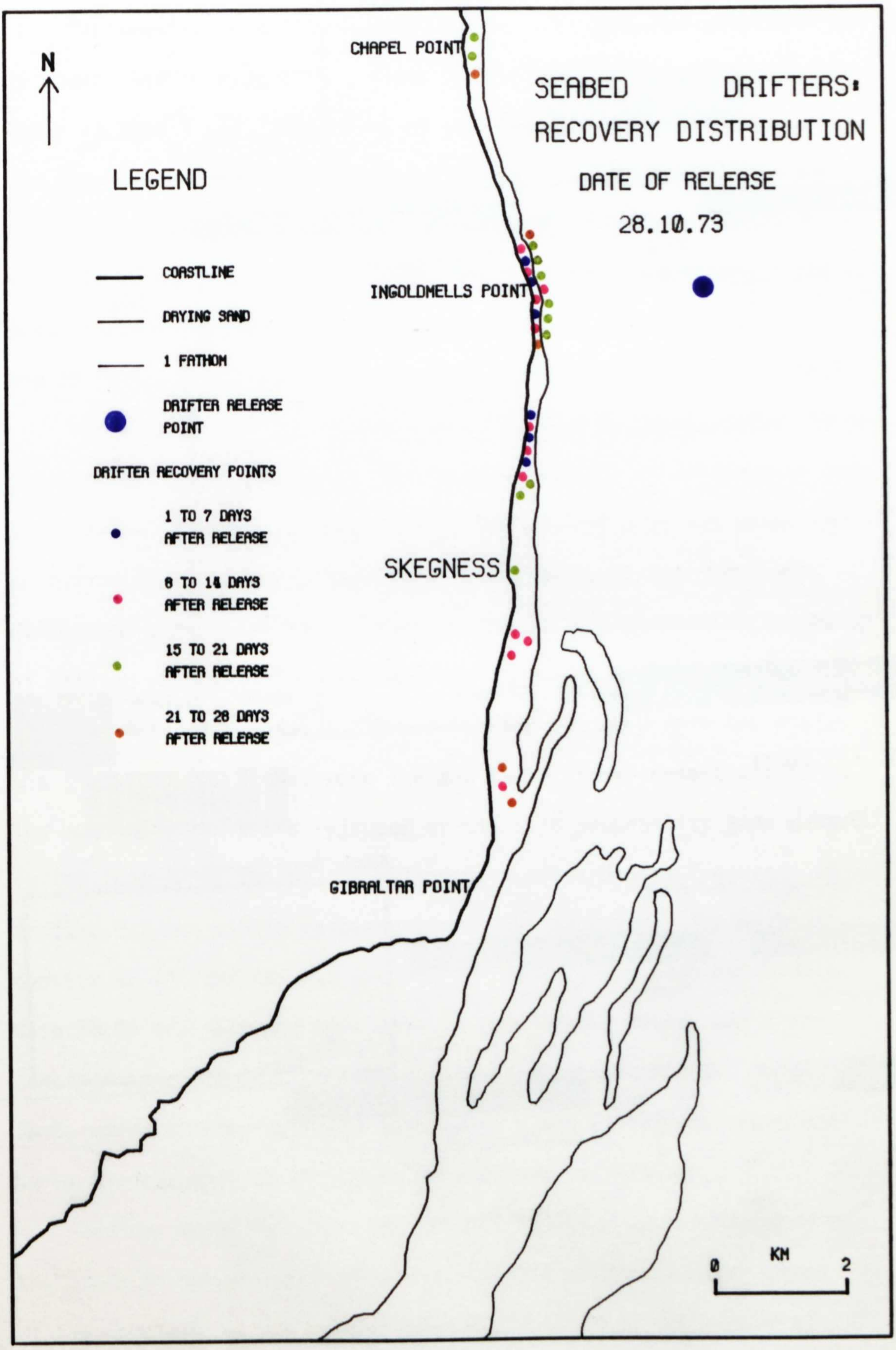
	RECOVERY TIME (DAYS) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AFTER 30	TOTAL PER ZONE	DENSITY DRIFTERS PER KM
MABELTHORPE																																0	0
CHAPEL ST.LEONARDS																	x	x				x									x	4	1.10
INGOLDMELLS		x			x	x					xx	xx	x				xx	x	x	xx		x					x					16	8.89
WINTHORPE		x		x			x					x	x				x	x														7	1.89
SKEGNESS PIER																	x															1	67
DERBY AVENUE											x		x	x																		3	1.82
SKEGNESS MIDDLE													x														x				x	3	2.22
GIBRALTAR POINT PATH																															xx	2	1.38
GIBRALTAR POINT SPIT																																0	0
WAINFLEET TO BOSTON																																0	0
EAST SIDE OF WASH																																0	0

DRIFT TO NORTH (Mabelthorpe – Ingoldmells)

DRIFT TO SOUTH (Winthorpe – Derby Avenue)

TOTAL RECOVERY 36

FIGURE 65



N
CHAPEL POINT
SEABED DRIFTERS:
RECOVERY DISTRIBUTION
LEGEND
DATE OF RELEASE
28.10.73
COASTLINE
DRYING SAND
1 FATHOM
DRIFTER RELEASE POINT
DRIFTER RECOVERY POINTS
1 TO 7 DAYS AFTER RELEASE
8 TO 14 DAYS AFTER RELEASE
15 TO 21 DAYS AFTER RELEASE
21 TO 28 DAYS AFTER RELEASE
INGOLDMELLS POINT
SKEGNESS
GIBRALTAR POINT
0 KM 2

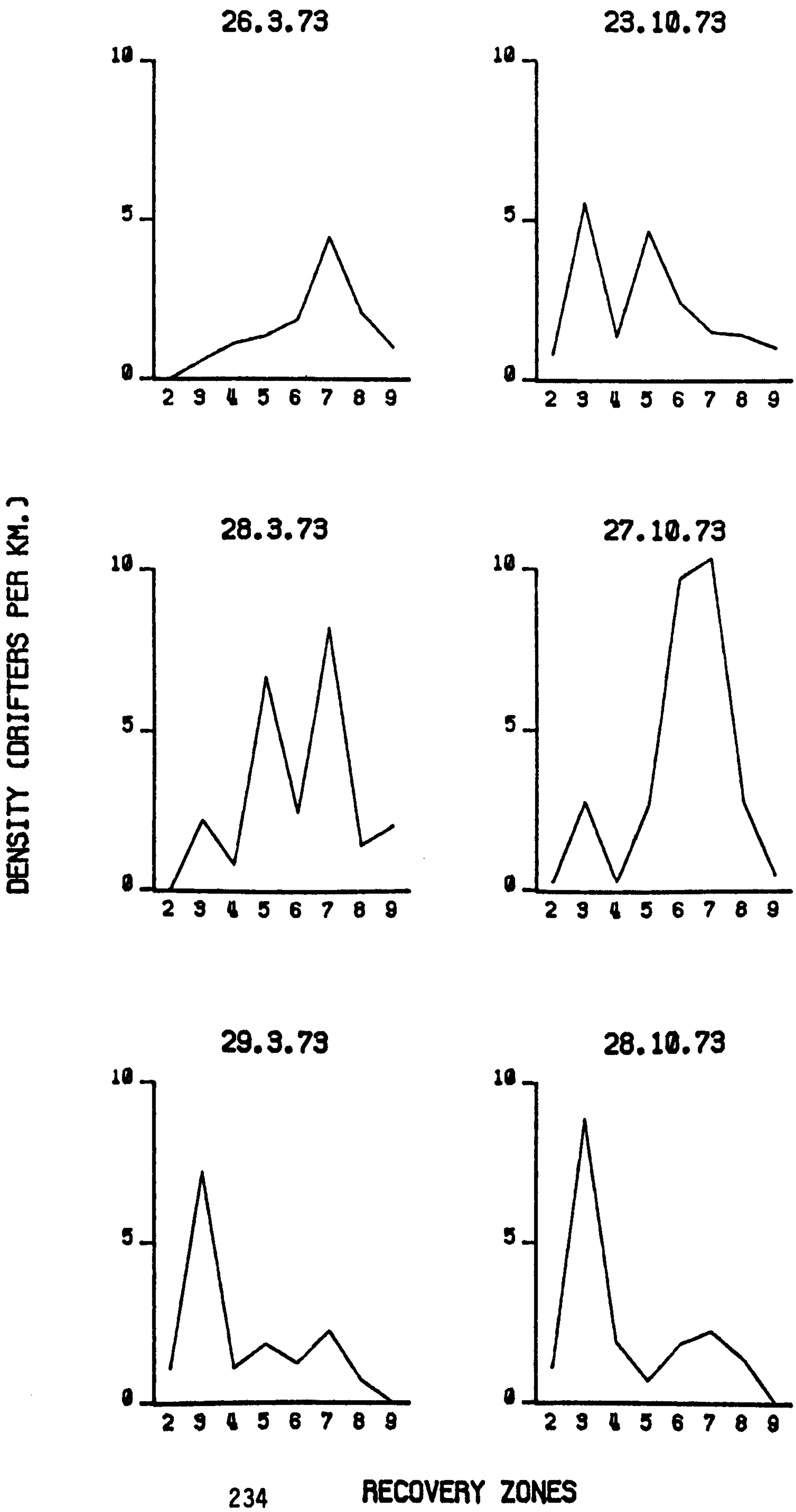
The density of drifters recovered in each zone for all releases is summarised in Figure 66. Peaks of drifter returns occur predominantly at zone 3 and 7 depending on the location of the release point. For the releases of 26.3.73, 28.3.73 and 27.10.73, made within the sandbank system, peak returns occur at zone 7. A minor exception is the release of 23.10.73 where peak returns occurred in zones 3 and 5. Both releases made outside the sandbank system, those of 29.3.73 and 28.10.73, had peak returns at zone 3 with minor peaks at zone 7.

The overall drifter recovery was analysed for preferential locations of drifter strandings. The overall density of drifters in each zone was calculated. (Table 22). A Chi-squared test was conducted on the basis of the null hypothesis that there was no significant difference between recovery zones as regards a preferential frequency of drifter returns. The test gave a χ^2 value of 102.87 with 7 degrees of freedom. Zones 1, 10 and 11 were excluded from the analysis since recovery rates were low and their linear extent was large. The null hypothesis was rejected at the 0.1% probability level, that is the inverse of the null hypothesis, a preferential frequency of drifter returns within recovery zones, was accepted. The maximum density of drifter returns occurred at zone 7, the Skegness Middle, with 28.88 drifters per km. Zone 3, Ingoldmells Point, had a recovery density of 27.22 drifters per km. The next highest zones in terms of drifter recovery were zones 5 and 6, Skegness Pier and Derby Avenue, with 19.39 and 18.00 drifters respectively.

Indices of daily net drift for all releases were calculated on the basis of the distance from the midpoint of the recovery zones of the drifters to the release point multiplied by the number of

FIGURE 66

DENSITY OF DRIFTERS RECOVERED PER ZONE FOR EACH RELEASE



OVERALL DRIFTER RECOVERY

TABLE 22

	TOTAL NUMBER OF DRIFTERS RECOVERED IN EACH ZONE	DENSITY (DRIFTERS PER KM.) IN EACH ZONE
MABELTHORPE	0	N/A
CHAPEL ST.LEONARDS	12	3.28
INGOLDMELLS	49	27.22
WINTHORPE	24	6.49
SKEGNESS PIER	27	18.00
DERBY AVENUE	32	19.39
SKEGNESS MIDDLE	39	28.88
GIBRALTAR POINT PATH	14	9.66
GIBRALTAR POINT SPIT	9	4.43
WAINFLEET TO BOSTON	2	N/A
EAST SIDE OF WASH	1	N/A

TOTAL RECOVERED 209

TOTAL RELEASED 300

OVERALL PERCENTAGE RECOVERED 69.66

drifters recovered in each zone on a particular day. The resulting information is shown in Table 23 and expressed graphically in Figures 67 and 68 for the releases of March and October respectively. It should be noted that the index does not reflect either the actual distance travelled by the drifter over the seabed or the path of the drifter but only the net drift from the release point to the recovery zone. However, it is interesting to note that in all cases except the release of 28.10.73, at Ingoldmells Point, the net drift is predominantly in a northerly direction.

DISCUSSION

The rate of drifter stranding along the section of the Lincolnshire Coast between Ingoldmells Point and Gibraltar Point appears to increase with winds blowing either offshore or from the north-northeast and increasing tidal current velocities as the tide approaches spring tide conditions. Both these environmental parameters could therefore, be responsible for sediment movement from the nearshore to the foreshore zones, but it is difficult, with the available information, to determine the relative importance of either parameter. The fact that sediment can be exchanged between nearshore sandbank systems and the adjacent foreshore has been confirmed by Jolliffe (1963). Beach surveys at Lowestoft, during a fluorescent tracer experiment on nearshore sandbanks, revealed that significant numbers of sediment particles were reaching the foreshore. Again it was not possible to differentiate the relative importance of wind, as it effects waves, and tidal currents as the causative agent of sediment movement, although heavy swells during the period of the survey suggested that

TABLE 23

NET DRIFT

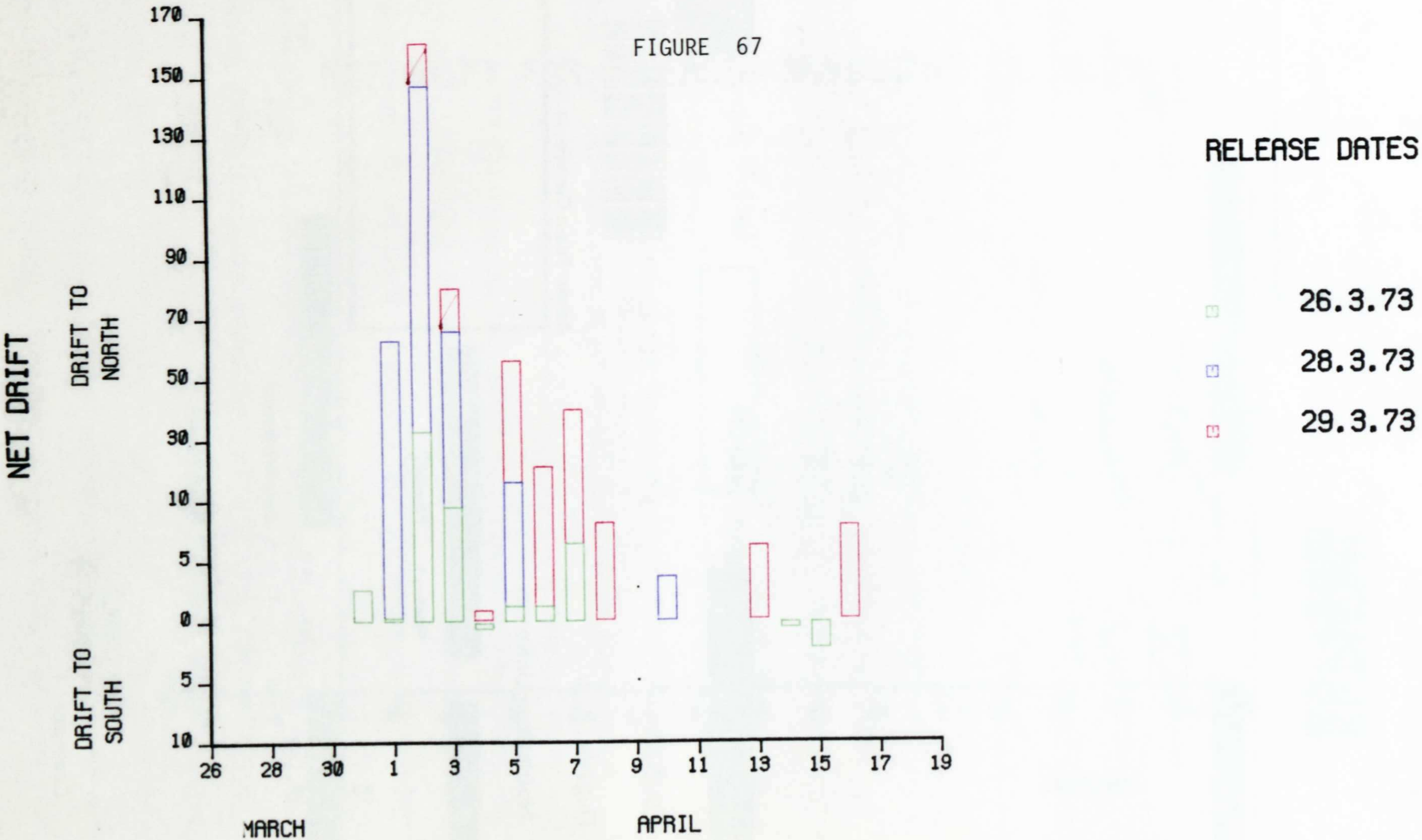
DAYS AFTER RELEASE

RELEASE DATE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
26.3.73					+2.90	+0.95	+33.25	+9.80	-0.55	+1.30	+1.90	+6.45							-0.55	-2.25										
28.3.73				+62.93	+113.78	+56.55		+19.48					+9.70																	
29.3.73				+14.87	+13.54	+0.88	+41.93	+19.92	+23.14	+8.10					+6.15			+7.80												
23.10.73			+2.90	+22.13	+1.90		+3.90	+19.50					+9.25	+9.25	+9.80	+12.65	+12.90	+15.70		+9.25	+8.70	+18.50	+11.78		+11.78		-0.55			
27.10.73										+30.53	+46.28	+1.13	+8.05	+11.15	+33.08	+15.10		+19.08					+10.98			+1.13			+2.48	
28.10.73		-2.30		-2.55	+0.25	+0.25	-2.55				-6.15	-2.05	-17.15	-6.65			-4.92	+0.53	+0.25	+0.50		+3.08					-7.95			

+ DRIFT TO NORTH

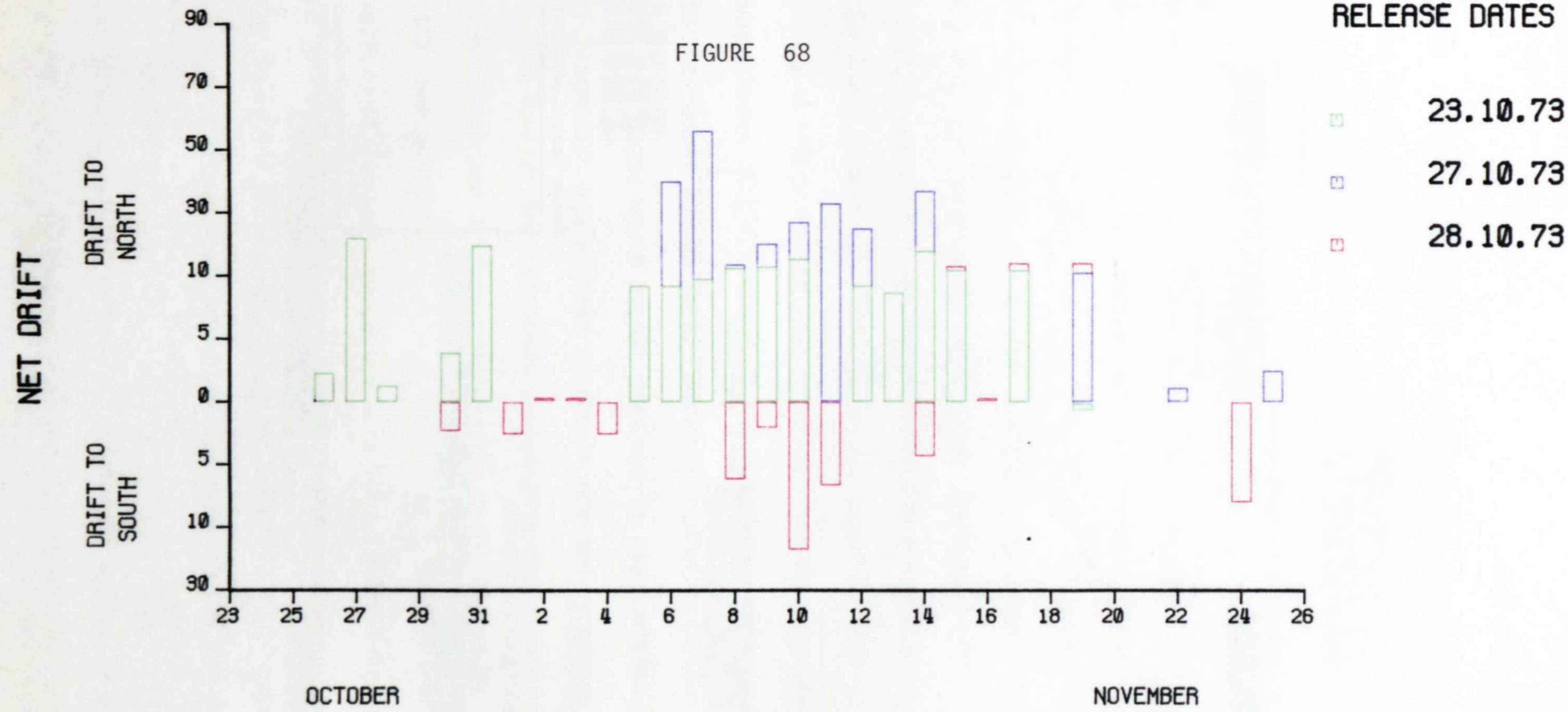
- DRIFT TO SOUTH

NET DRIFT FOR RELEASES BEGINNING 26.3.73



NET DRIFT FOR RELEASES BEGINNING 23.10.73

FIGURE 68



waves were in some measure responsible. However it was concluded that this evidence in no way invalidates the hypothesis of Robinson and Cloet (1953) that onshore migration of sand may be due to the movements of sandbanks.

Robinson (1964) conducted a Woodhead Seabed Drifter experiment around Spurn Point, north of the Humber estuary. Two major concentrations of drifters were reported on the Lincolnshire Coast. The northerly concentration occurred around Saltfleet Haven where a nearshore ebb-flood sandbank system has developed and created a convergence of tidal flow towards the coastline. The southerly concentration occurred between Skegness Pier and Gibraltar Point where 10 drifters were recovered. This evidence, together with the recovery of two drifters in the area offshore from the Lincolnshire Coast, suggested a considerable residual drift of sediment southwards from the Humber to the Wash. Sediment migrating southwards in the nearshore zone would become involved in the sandbank system south of Skegness. Again these sandbanks created a convergence of tidal flow towards the foreshore encouraging the stranding of drifters. Two of the ten drifters reached the foreshore south of Skegness within one month of release whereas others arrived much later. This pattern of recovery suggested that some drifters became involved in the sediment circulation around the sandbanks prior to stranding on the foreshore under suitable wind and tide conditions and that the sandbanks acted as an important sediment source for the foreshore.

The present study in which drifters were released within or near the sandbank system largely confirmed the above conclusions but with detail modifications. The drifters released within the sandbank system were stranded on the foreshore predominantly between Skegness Pier and the location at which the Skegness Middle sandbank reaches the foreshore. This is a location where a flood channel is directed towards the foreshore from the nearshore zone and is terminated in a southerly direction by the junction of the Skegness Middle and the foreshore. The tidal currents associated with the development of this channel would also bring drifters and sediment towards the foreshore zone at this location. Relatively few drifters were recovered from the foreshore zone south of Skegness Middle despite the fact that another flood channel, the Wainfleet Swatchway is directed towards the foreshore at this location. However, unlike the channel between the foreshore and the Skegness Middle the Wainfleet Swatchway does not show a marked tendency to shallow towards the foreshore, and it opens in a southerly direction into the Boston Deep. Drifters and sediment moving in a southerly direction along the Wainfleet Swatchway would, therefore, be likely to be reintroduced into the northerly residual flow in the Boston Deep rather than become stranded on the foreshore. The blind channel between the foreshore and the Skegness Middle would appear to be the main route along which sediment is transported from the nearshore to the foreshore zones.

Rather surprisingly the second largest concentration of drifters occurred at Ingoldmells Point some 5 km. north of the sandbank system, although very few drifters moved north of this location into Chapel Bay. The stranding of drifters on the foreshore at Ingoldmells Point is most commonly associated with releases made outside the sandbank system although all releases made within the sandbank system also provided some drifters which were stranded at this location. This pattern of recovery confirms the net northerly drift of sediment in the nearshore zone in the Skegness area suggested in Chapter 8, although it would appear that it has a much larger areal extent than could be predicted on the basis of the evidence available for the construction of the sediment movement model. It would appear, therefore, that there is a net northerly drift of sediment as far north as Ingoldmells Point. The net southerly drift along the Lincolnshire Coast from the Humber suggested by Robinson (1964) could meet the net northerly drift of the Skegness area in the vicinity of Ingoldmells Point. Such an opposition of net tidal movements could possibly account for the stranding of drifters at this location since there is no evidence of convergence of tidal currents towards the foreshore. It is possible that drifters released from the sandbank circulation south of Skegness could migrate northwards to Ingoldmells Point to be retained in the area until either suitable wave or tidal conditions existed for movement to the foreshore and subsequent stranding. The sediment movement pattern in the vicinity of Ingoldmells Point is, therefore, probably similar to the bedload convergences described by Stride (1971) on a much larger scale in the North Sea and the English Channel.

A few of the drifters released offshore from Ingoldmells Point migrated south to the area immediately south of Skegness Pier. It would appear, therefore, that there is some mechanism for transferring drifters in a southerly direction against the dominant net northerly drift. In other words, in terms of the nearshore zone, there must be a circulation in the area with a strong northerly moving component complemented by a weaker southerly moving component. The location of these components in either time or space is not known. There are two possible explanations for the southerly movement of drifters in the area. Firstly, evidence of the accretion of sediment on the northern sides of groynes on the foreshore between Ingoldmells Point and Skegness Pier suggest a net southerly movement of sediment along the foreshore under the influence of dominant waves from tne north-east. It is possible that drifters become involved in this movement immediately seaward of the foreshore zone. Secondly, Robinson (1964) suggested that the central channel of the Wash, the Lynn Deep, is a flood channel. Drifters released offshore from Ingoldmells Point could have moved seaward and become involved in this net southerly drift to be captured at a later stage by the tidal circulation system associated with the sandbanks south of Skegness. Once in the sandbank system the drifters would be subject to the same movement patterns as the drifters released within the system and become involved in the net northerly drift in the nearshore zone to be stranded later on the foreshore near the Skegness Middle sandbank. Eight of the fifteen drifters recovered at Ingoldmells Point from the release made offshore from this location took more than 15 days to reach the foreshore. These drifters could have followed the path described above, a movement pattern which would help to account for the relatively long period of time taken by the drifters to migrate a relatively short distance. The circulation pattern described above, a southerly net drift seaward of the net northerly drift in the nearshore zone, could also help to account for the stranding of drifters on the foreshore between Skegness Pier and Gibraltar Point which were released offshore from Spurn Point (Robinson, 1964). The drifters recovered from the foreshore at this location could have by-passed the convergence in the vicinity of Ingoldmells Point, being carried south by the seaward southerly drift.

The overall recovery rate of drifters released in the six experiments was 69.66%. This recovery rate is similar to 76% recorded by Phillips (1970) in Morecambe Bay and 70% recorded by Riley and Ramster (1972) for an experiment off the Norfolk Coast. All these areas are characterised by tidal current ridges, ebb and flood channels and convergence of tidal flow towards the foreshore at specific sites. These high recovery rates substantiate the theory advanced in the descriptive sediment movement model that sediment circulation associated with these features is essentially closed and that tidal current ridges represent sediment traps of a high order of efficiency.

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CHAPTER TEN

HISTORICAL DEVELOPMENT OF THE SANDBANKS AND CHANNELS.

Swift (1975) noted that the development of tidal current ridges tends to be cyclic rather than linear and also noted the relative stability of these bedforms. Rates of ridge movement and evolution are slow and ridge stability is sufficient that the course of 17th-century Dutch naval battles can be traced on modern maps (Brouwer, 1964). Such stability is probably characteristic of all large scale current parallel bedforms particularly the wind parallel dunes of deserts which may have taken 10,000 years to develop (Wilson, 1972). In other words, tidal current ridges appear to be hydraulically maintained sand traps of a high order of efficiency (Swift, 1975).

Several studies of the changes in size, shape and position of tidal current ridges through time have been undertaken on the basis of documentary evidence from Admiralty and other bathymetric charts to establish both the causes of changes and the stages of development or evolutionary history of such bedforms. Robinson (1956, 1960) suggested changes in size, shape and position of tidal current ridges are probably related to changes in sediment supply, particularly the availability of transportable material, the relative strength of opposing tidal current streams and the influence of episodic storms when wave action may play a significant part.

Cloet (1954a, 1954b) studied the evolution of tidal current ridges in the southern North Sea and the Persian Gulf. An aerofoil was fitted to the outer margin of the Goodwin Sands and the movement of the bank analysed in relation to the lengths of the major and minor axes, the angle enclosing the nose of the sandbank and the angle between the major axis and the meridian. The causes of the changes in these shape characteristics were considered to be related to variations in the strength of tidal currents and the availability of transportable material. The characteristic shape of contiguous parabolae of tidal current ridges was thought to resolve into three ridges, the middle termed mid-channel, when sediment supply was reduced and the sandbanks at the heads of the channels were removed. The relative development of the linear ridges was then dependant on the relative strength of opposing tidal streams. Variations in the relative strength of opposing tidal streams were also considered to be responsible for the rotation of the Goodwin sands relative to the meridian.

Robinson (1960) analysed changes in the configuration of the Edinburgh channels in the Outer Thames estuary which have been surveyed every two or three years since 1926 on a scale of six inches to a nautical mile. To assess changes in the configuration of the channels isallobath maps, showing areas of equal changes of depth, were constructed. These maps showed that changes tended to take place along narrow belts bordering neighbouring sandbanks, particularly Shingles Patch. Areas of belts of shoaling and deepening along the margins of Shingles Patch were plotted to show the growth stages of the sandbank through time. The changing shape of Shingles Patch was explained on the basis of an aerofoil, a shape offering least resistance to flow. Theoretical variations in the pressure of flow associated with a double aerofoil were applied to Shingles Patch and it was found that axes of shoaling occurred in areas of theoretical negative pressure. Conversely, axes of deepening occurred in areas of theoretical positive pressure.

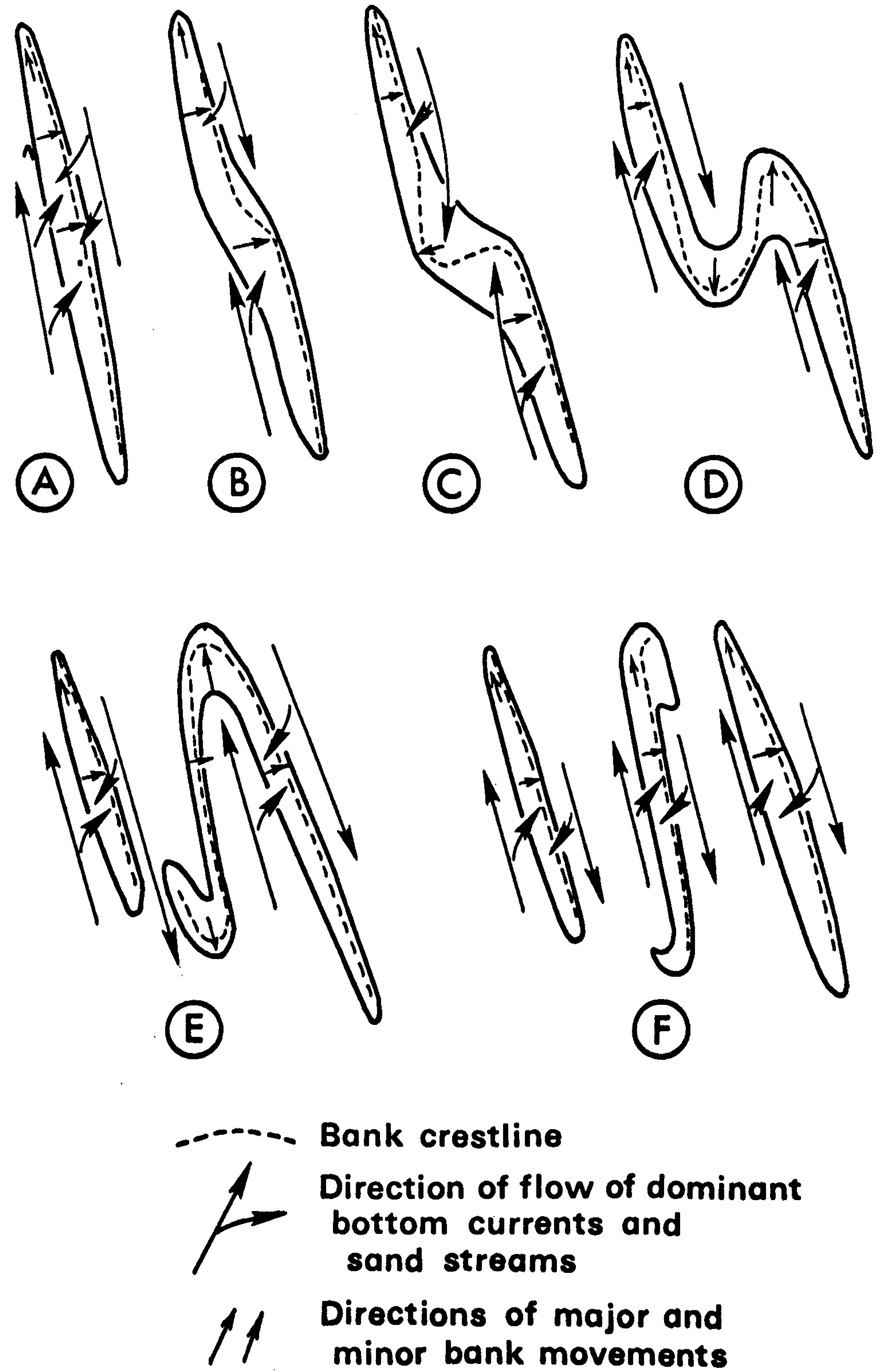
Following a study of tidal current ridges off the Norfolk Coast

Caston (1972) proposed a sequence of development for tidal current ridges, similar to that of Cloet (1954), related to the direction of dominant tidal current flow and sand transport direction. The sequence (Figure 69) was considered to begin with a linear tidal current ridge (A) which would eventually lose the straight outline, possibly because of unequal rates of sediment transport laterally across the sandbanks. A slight kink would develop which would be emphasised by opposing tidal currents on either side of the bank (B and C). The kink then develops into a double curve and the cross-sectional asymmetry changes from one side of the bank to the other (C). The double curve develops into an incipient pair of ebb and flood channels (D) which lengthen until the oblique bank between the two channels becomes parallel with those on either side (E). The parabolic noses of the banks are removed leaving three linear tidal current ridges instead of one (F).

Kestner (1970) analysed the movement of the First Clark Wharf Spit in Morecambe Bay based on Admiralty Charts from 1845 to 1968. As this sandbank moved eastwards at a rate of 100 feet per annum it left behind a flat shallow sandy area with no marked drainage channels. Beginning in 1913 a new sandbank, the Second Clark Wharf Spit, developed on this flat surface which was interpreted as the beginning of a new cycle of bank movement similar to that of the intial sandbank. In other words, Kestner (1970) envisaged a cycle of tidal current ridge movement not necessarily related to changes in the shape and form of the sandbank.

Tidal current ridge stability was emphasised by Smith (1969) who analysed the movement of Middle Ground in Vineyard Sound, Stages in the growth and development of Tidal Current Ridges

FIGURE 69 (After Caston, 1970)



Massachusetts. Unlike the areas off the Norfolk Coast and in Morecambe Bay transportable sediment to maintain tidal current ridge growth and development is not available in this area. Middle Ground appears to have been isolated, receiving no sediment from the surrounding land masses or sea floors, during the last 6,000 years. Some loss of sediment occurs at the western end of the sandbank. Middle Ground has responded to this loss by maintaining height at the expense of width with no significant movement trends.

Robinson (1956) discussed changes in the submarine morphology of the Thames estuary, Liverpool Bay, the Ribble estuary, Morecambe Bay and the Wash. The dominant hydrographic feature of the Wash is the axial Lynn Deep which is seperated from the Lincolnshire coast by Roger Sand and Long Sand. The Freeman and Parlour Channels connect the Lynn Deep with the Boston Deep which shallows in a seaward direction and is terminated by the complex of sandbanks comprising the Inner and Outer Knocks and the Inner and Outer Dogs Heads. On a chart of 1828 the Freeman Channel was shown as a shallow passage with a minimum depth at low water of 6 feet. Between 1871 and 1890 the bed of the channel was scoured and deepened, possibly related to the straightening of the lower reaches of the Rivers Witham and Welland. Since 1900 the Freeman Channel has remained relatively stable both in terms of position and depth and has a configuration termed a neutral channel, that is deepest in the middle section and shallower at each end, possibly being in transition from a flood to an ebb channel.

In the area immediately south of Skegness Robinson (1956) noted the relative stability of the sandbanks and channels enclosing the northern, seaward, end of the Boston Deep since 1828, particularly the Parlour Channel and Wainfleet Swatchway which are flood channels.

A study was made of the changes of area of sandbanks and channels, based on bathymetric charts of the Skegness area, made available by the Admiralty at Taunton, surveyed in 1871, 1910, 1918,1924, 1930, 1935 and 1958. (Figures 70 to 76). The key to these maps is shown on Table 24. Maps similar to the isallobath maps of Robinson (1960) were constructed to determine area changes between survey periods of channels and sandbanks in the Skegness area. Changes in area at the 3 fathom depth level were found to represent changes in channel area and changes in area at the 1 fathom depth level were found to represent changes in sandbank area. A key is shown as Table 25 for the maps of area change. The major features of the area changes of sandbanks and channels will be described for the periods between surveys :-

1. 1871 - 1910 (Figures 77 and 78). In this period there was some loss of area at the northern end of Long Sand which was associated with the growth and deepening of Parlour Channel. The northern end of the Boston Deep shifted in a south-easterly direction and the link between the Outer Knock and the Outer Dogs Head shallowed with some loss of area at the northern tip of the latter sandbank. The northern entrance to the Wainfleet Swatchway widened slightly and the southern entrance into the Boston Deep from this channel also extended and deepened.

2. 1910 - 1918 (Figures 79 and 80). The Parlour Channel again deepened and migrated south at the expense of Long Sand. The Inner Dogs Head extended south to occupy the former position of the Parlour Channel and also extended in a westerly direction.

TABLE 24

Drying sand on sandbanks	① Inner Knock
	② Outer Knock
Drying sand on beach	③ Outer Dog's Head
	④ Inner Dog's Head
1 Fathom	⑤ Long Sand
	Ⓐ Wainfleet Roads
3 Fathoms	Ⓑ Boston Deep
5 Fathoms	Ⓒ Parlour Channel
Skegness Pier	

FIGURE 70

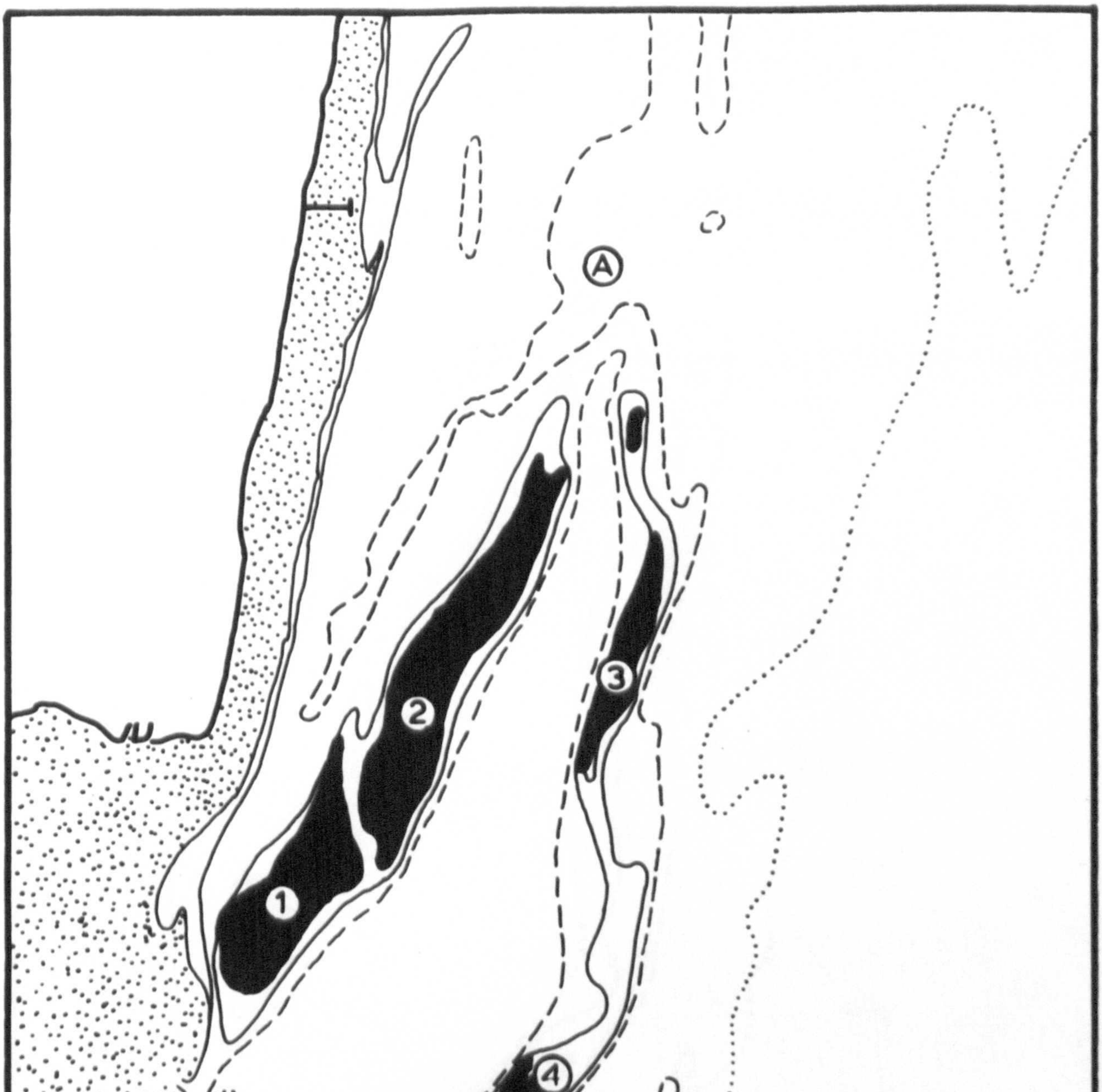


FIGURE 71

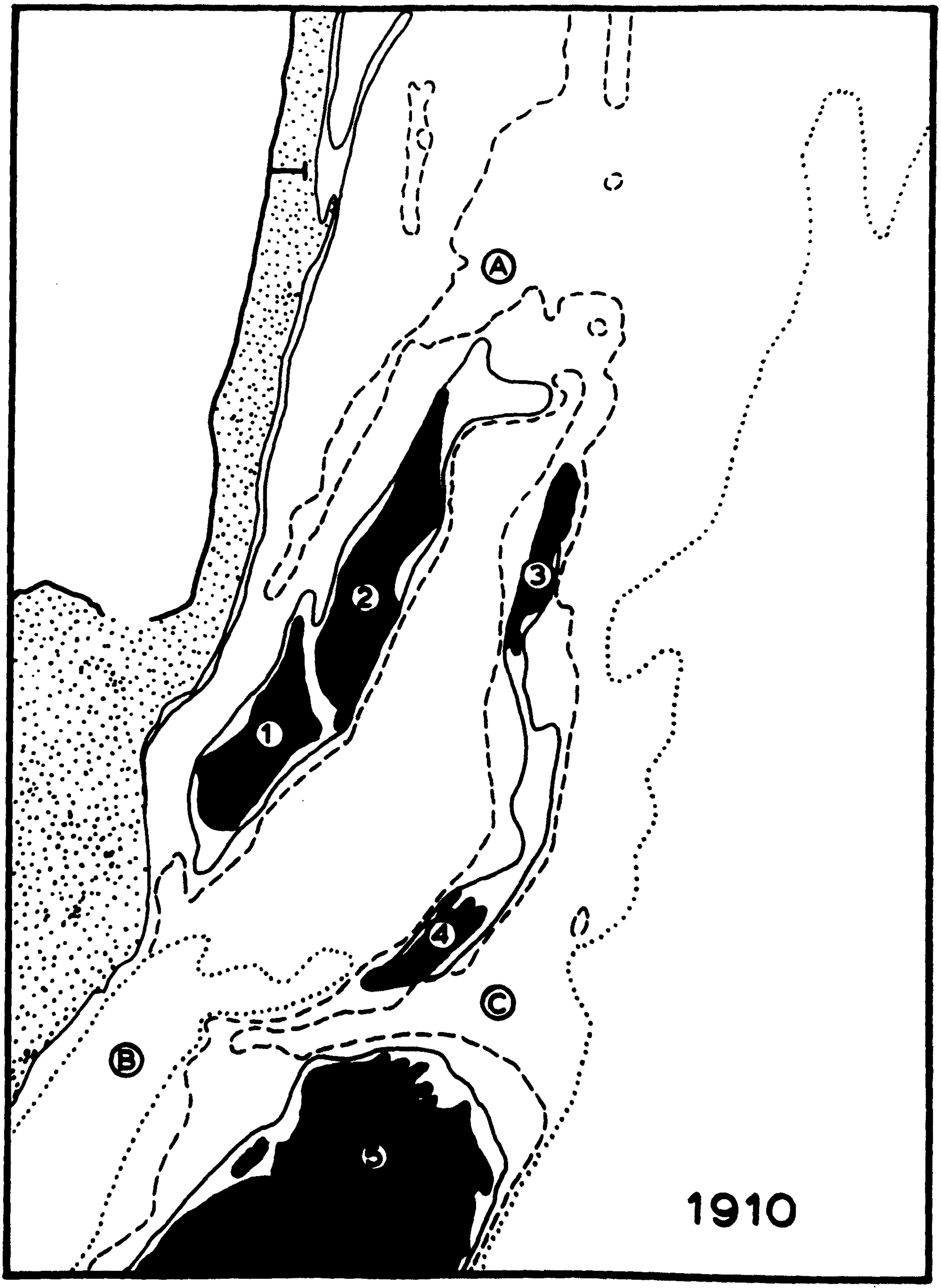


FIGURE 72

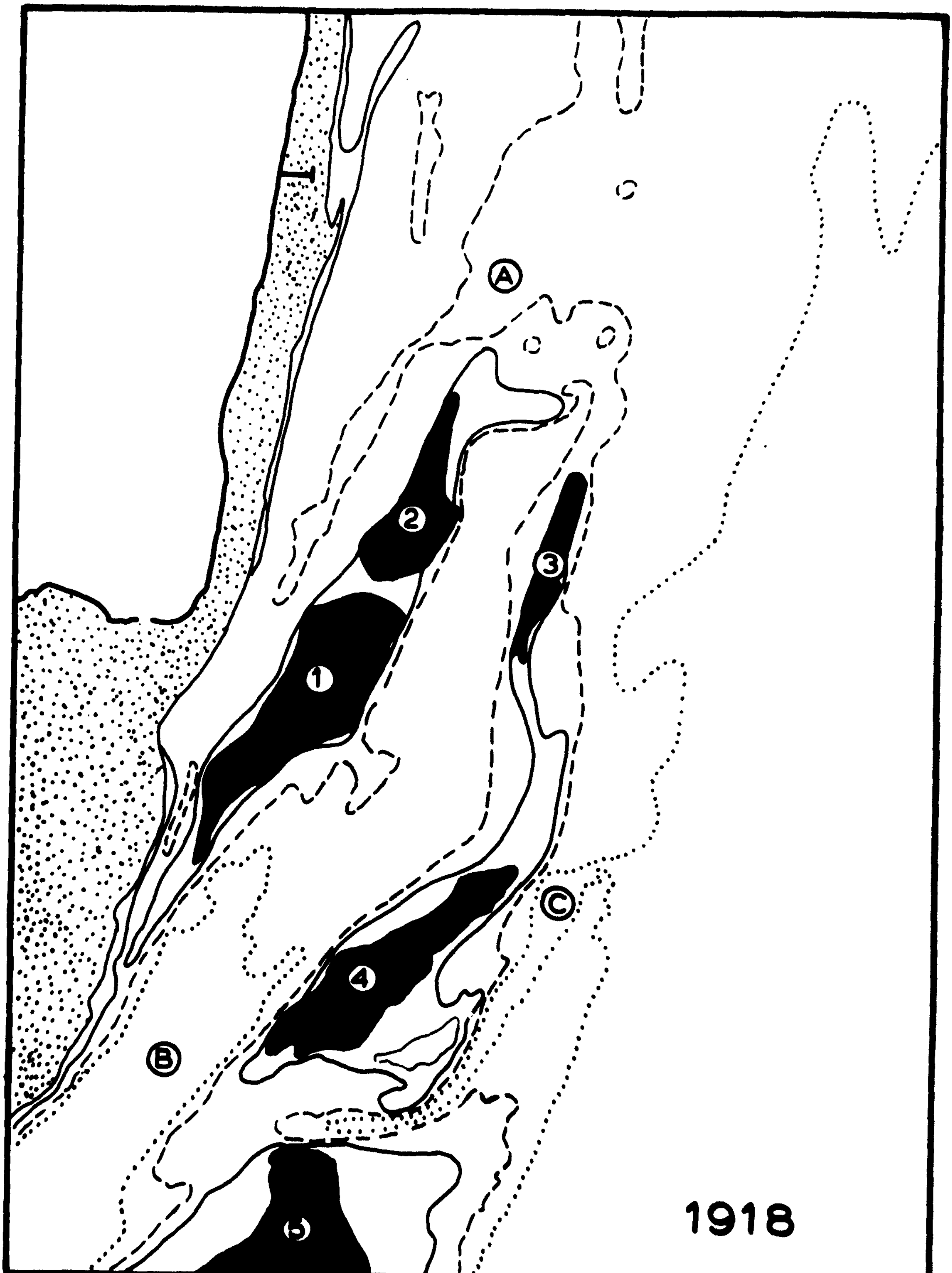


FIGURE 73

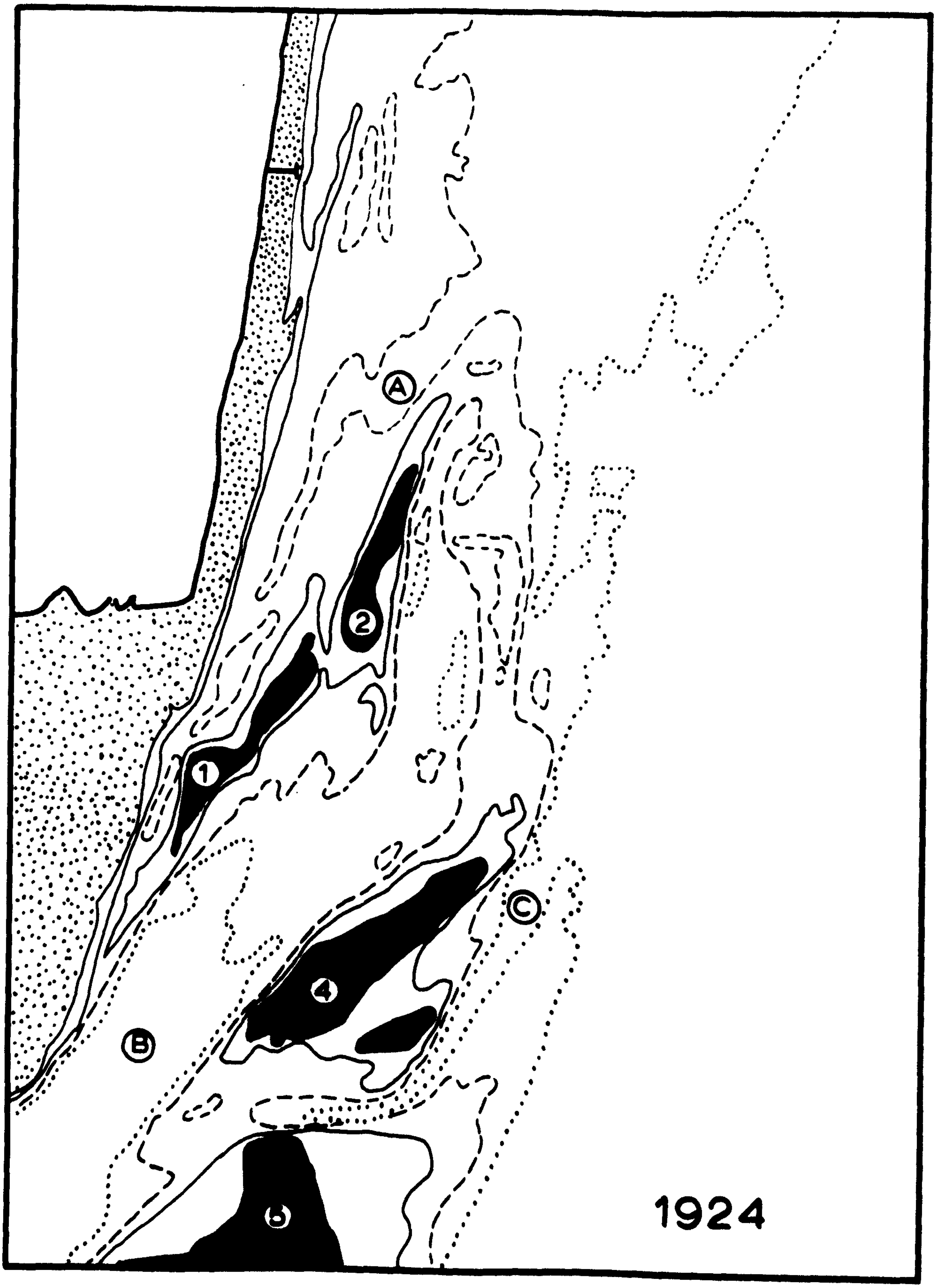


FIGURE 74

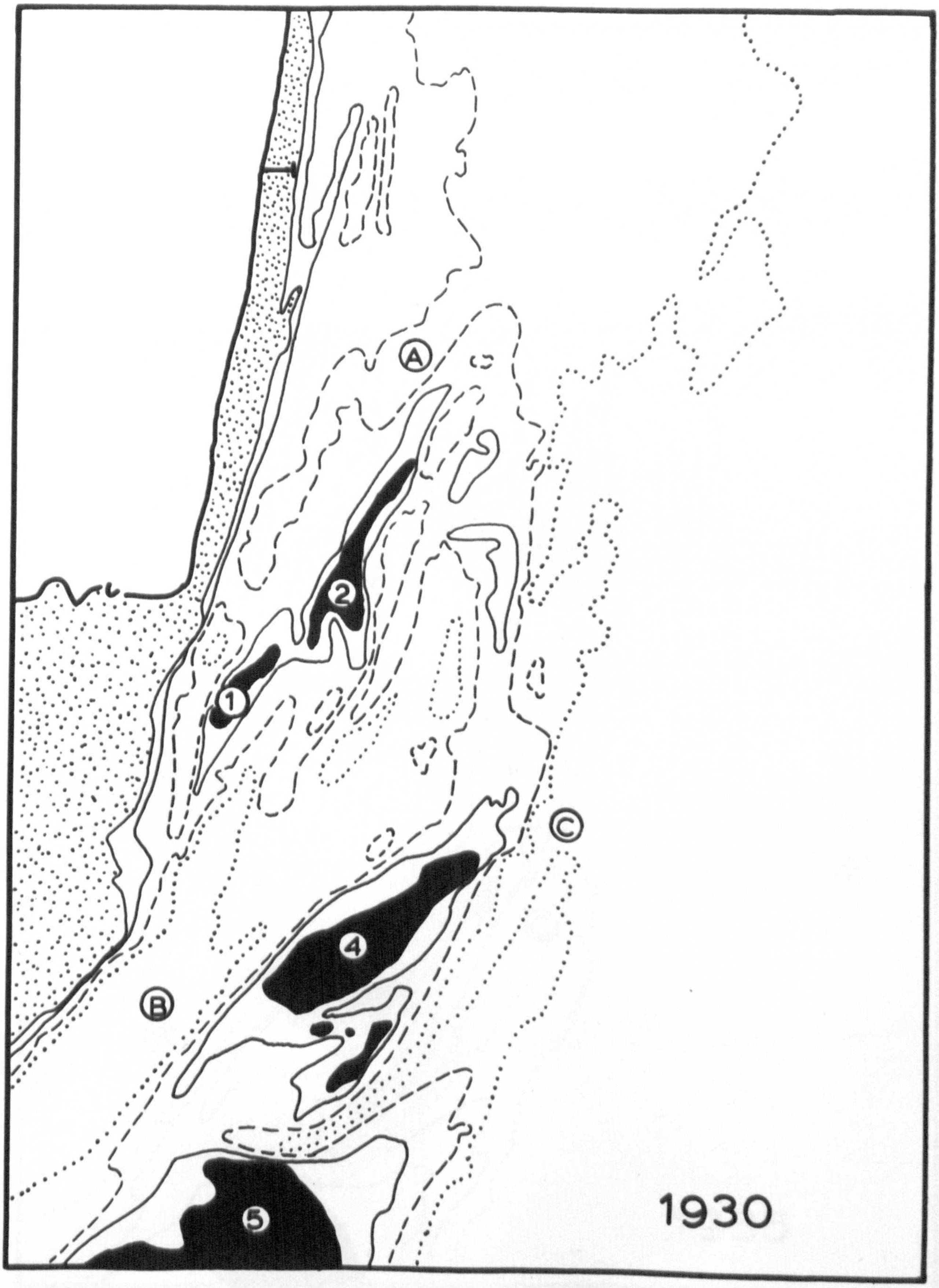


FIGURE 75

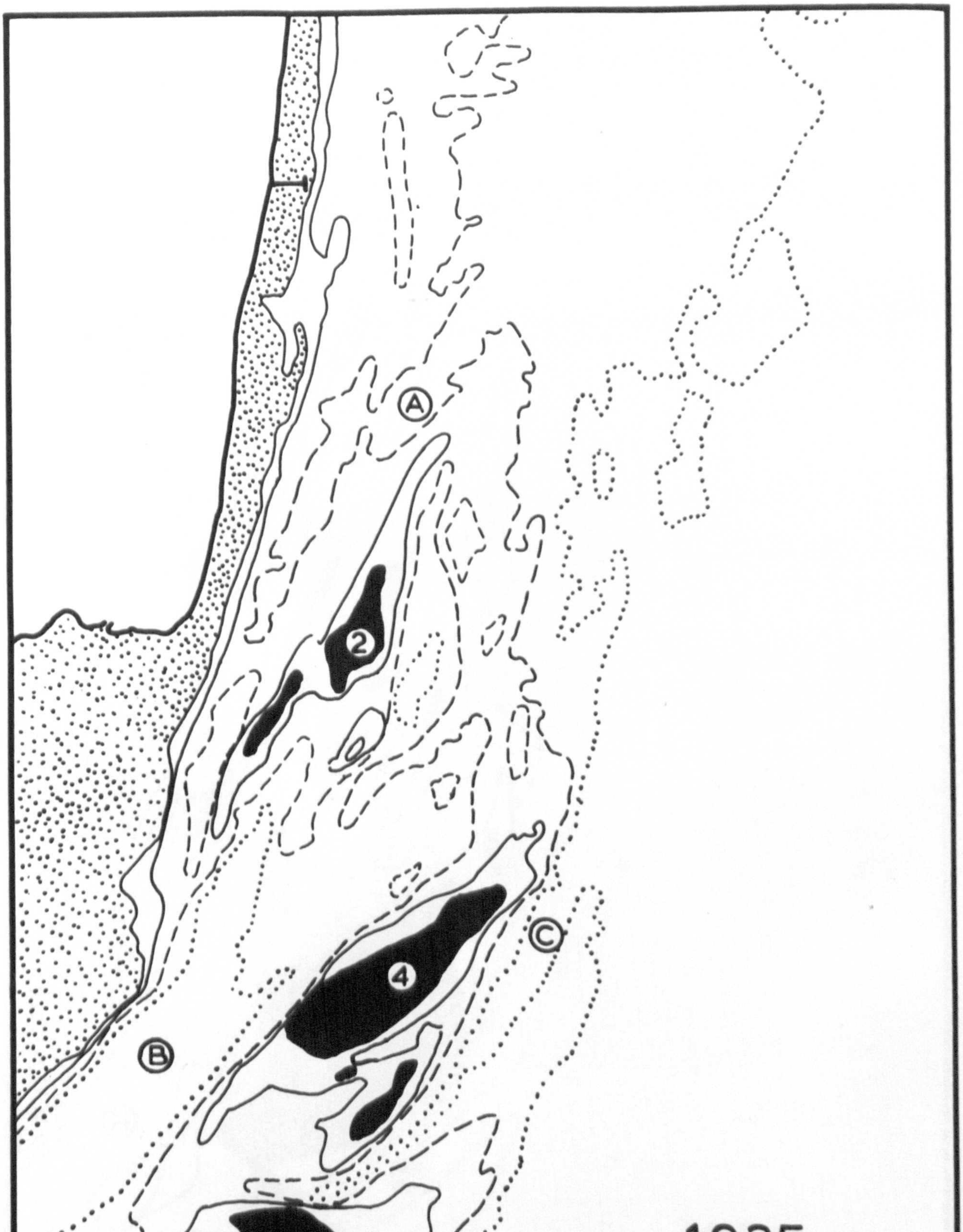


FIGURE 76

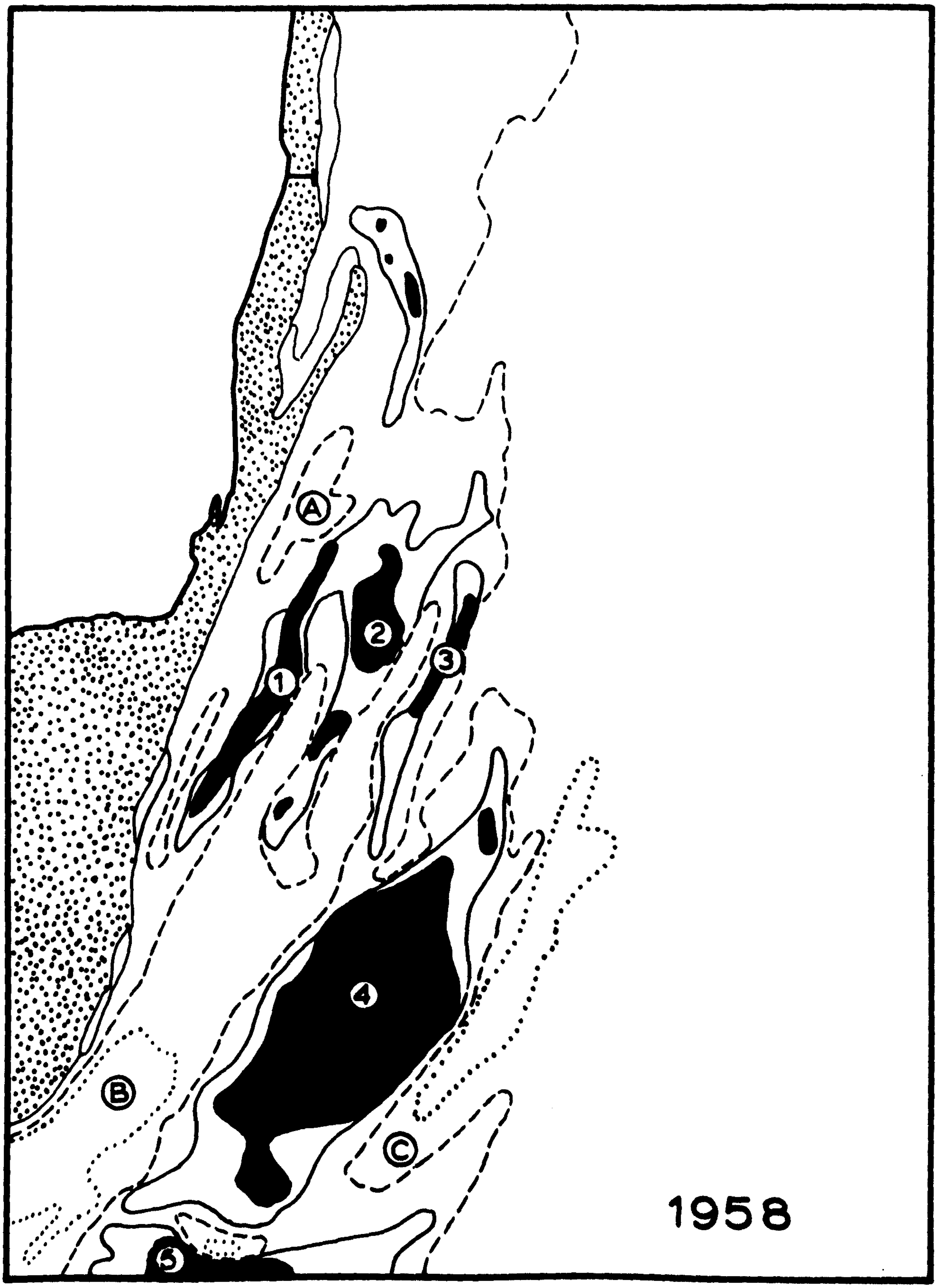


TABLE 25

Maps of area Change.

Explanation of Figures 77 - 88

Areas shaded black indicate areas where deepening has occurred between survey periods.

Areas diagonally shaded indicate areas where shallowing has occurred between survey periods.

Scale of maps Approximately 1 : 35,000

FIGURE 77

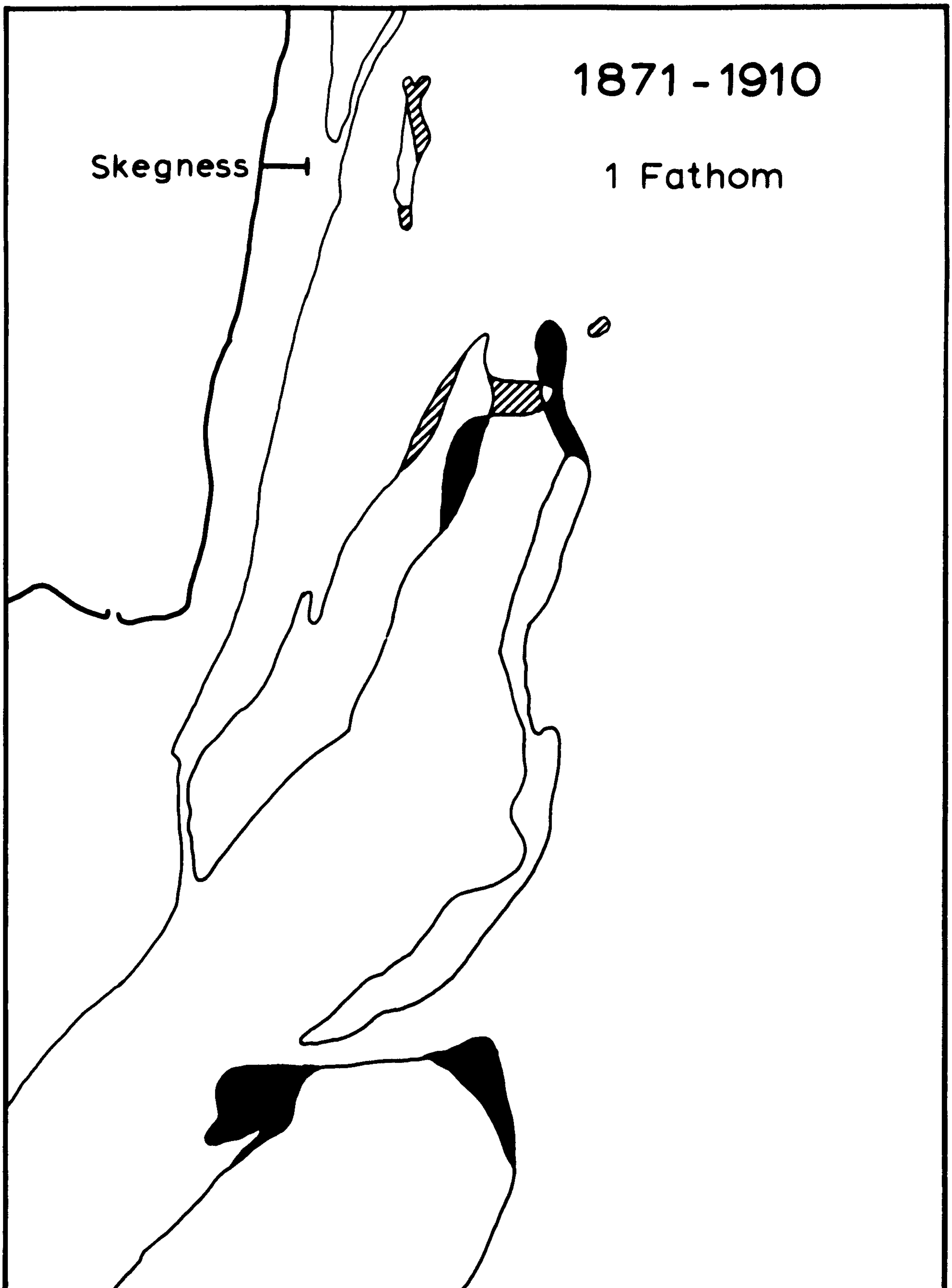


FIGURE 78

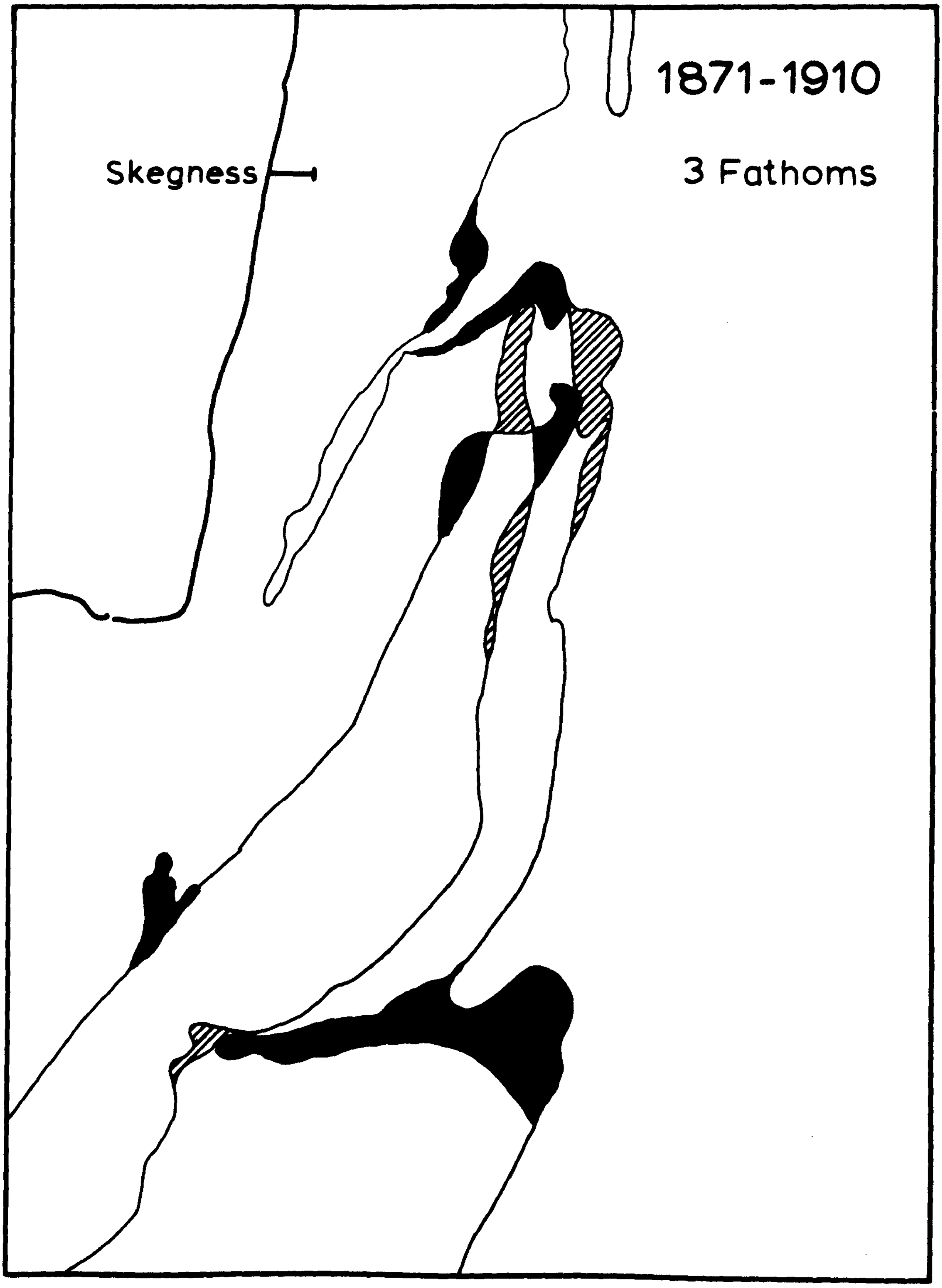


FIGURE 79

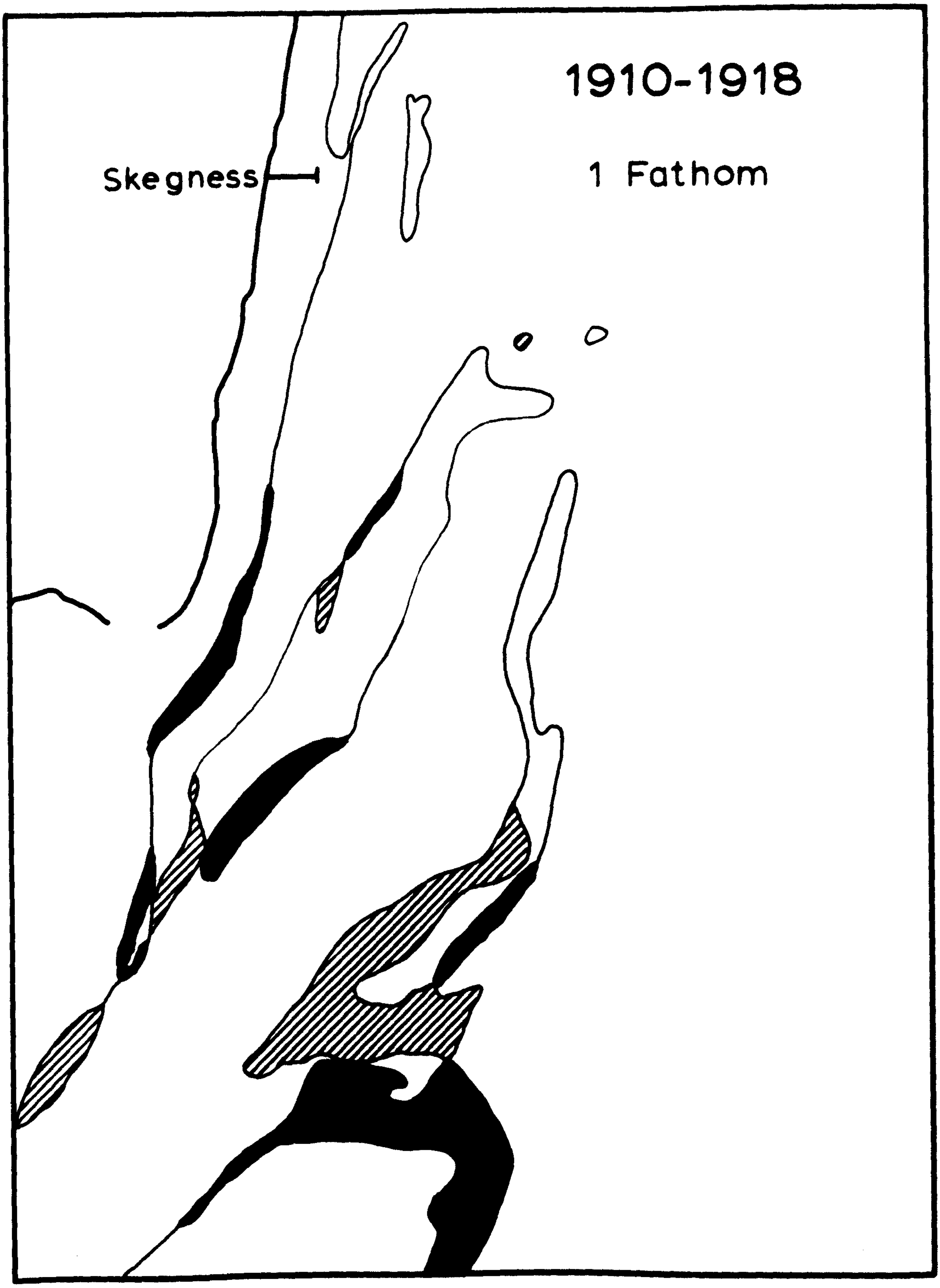


FIGURE 80

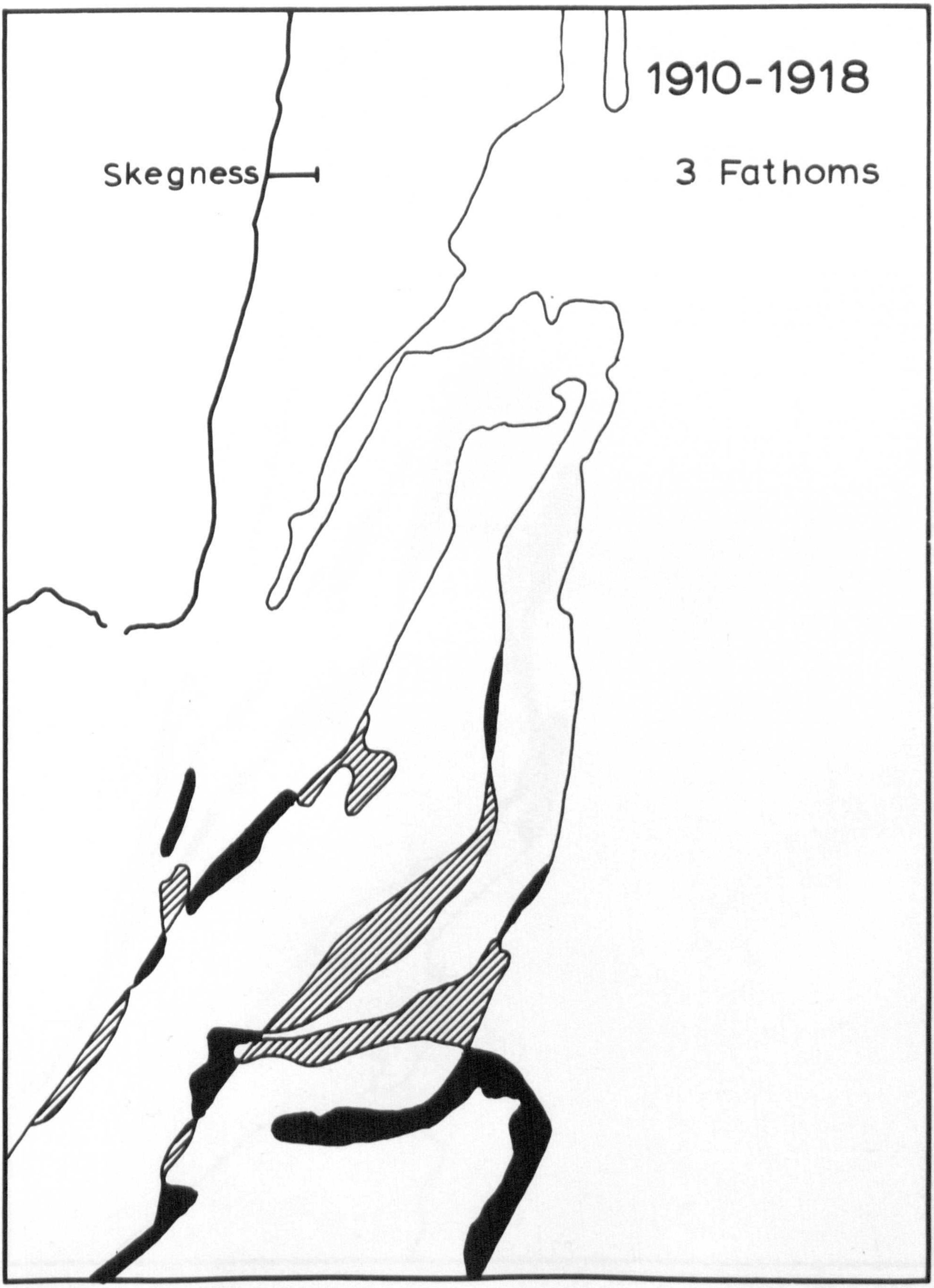


FIGURE 81

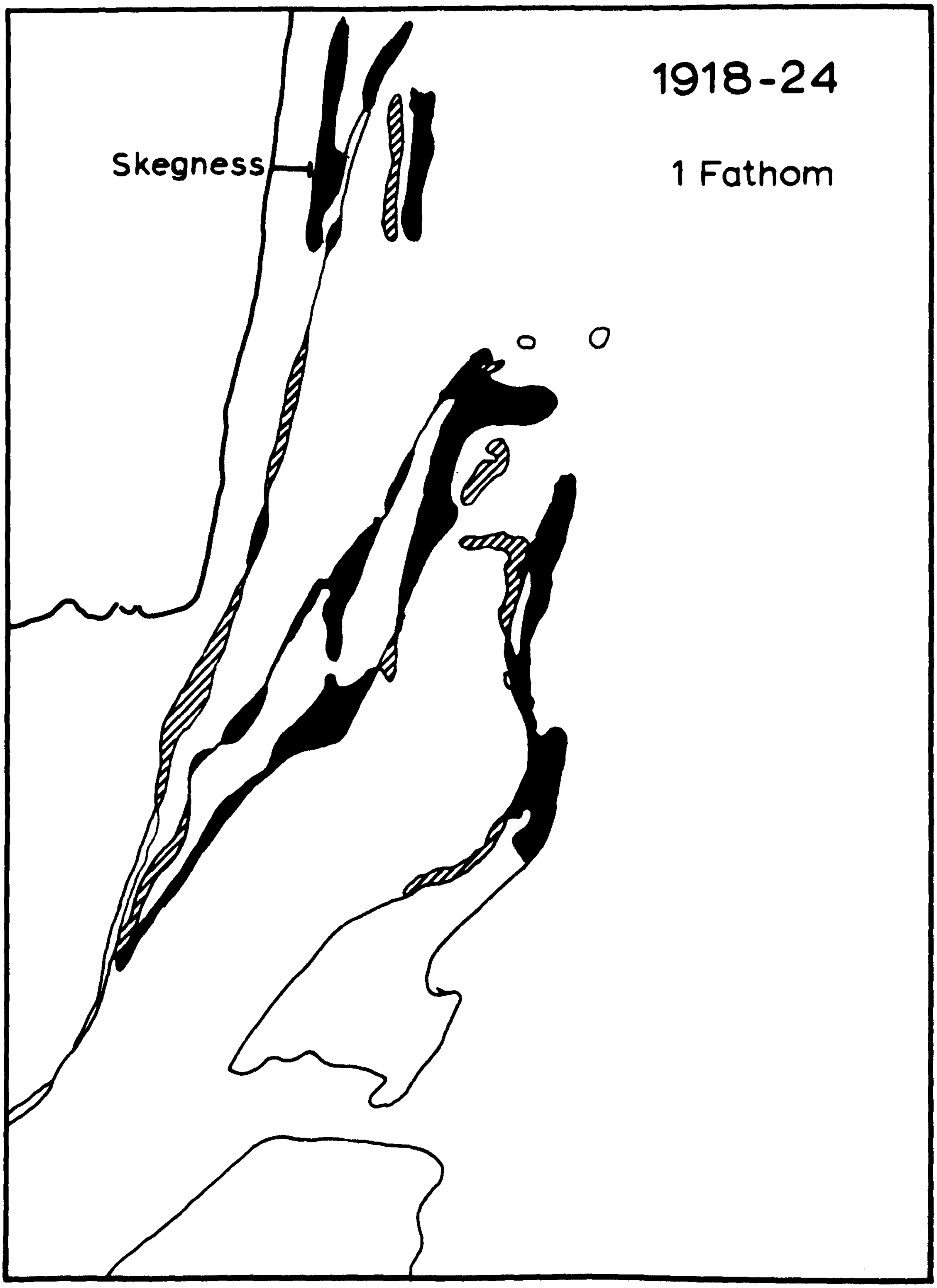


FIGURE 82

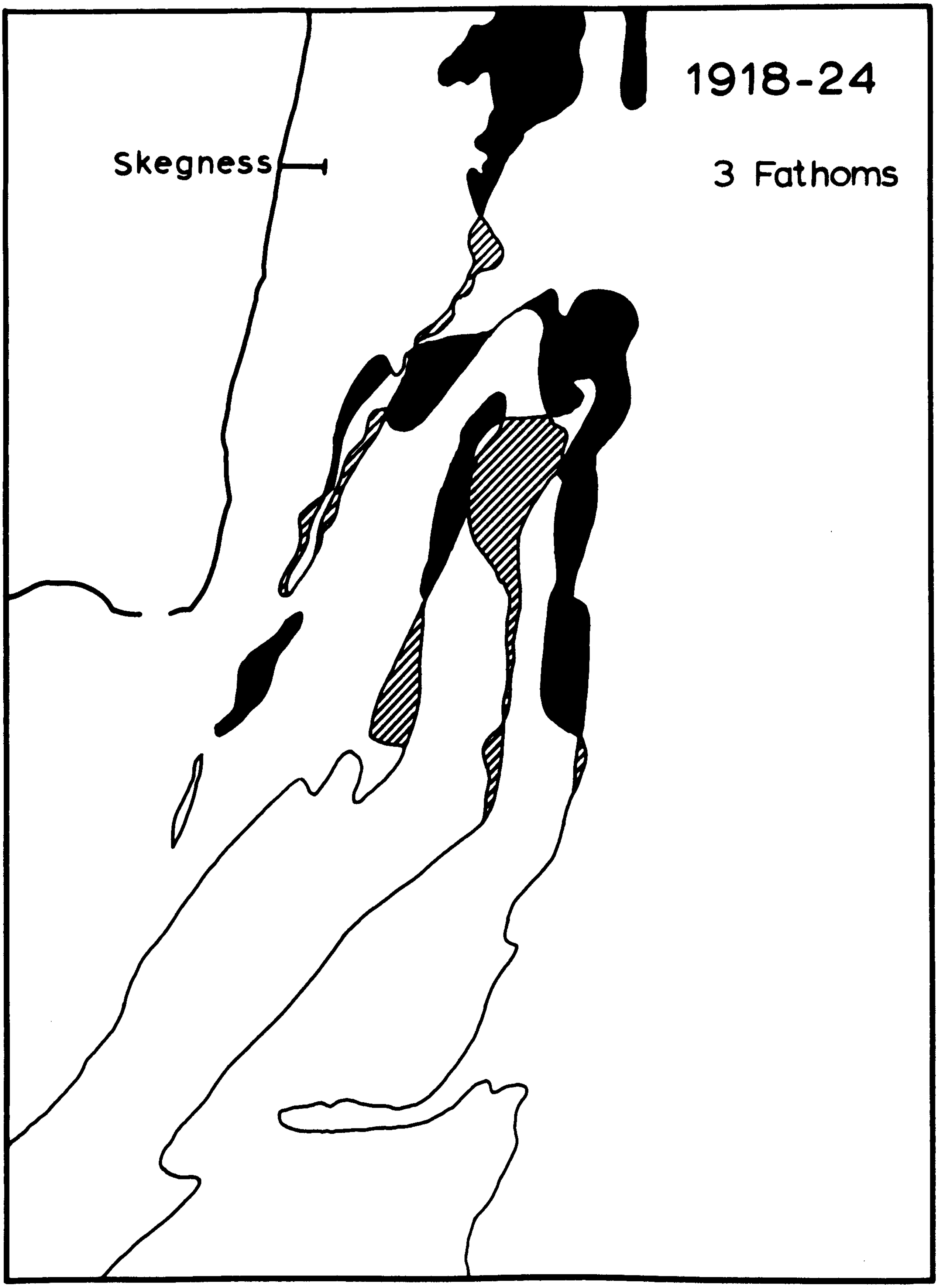


FIGURE 83

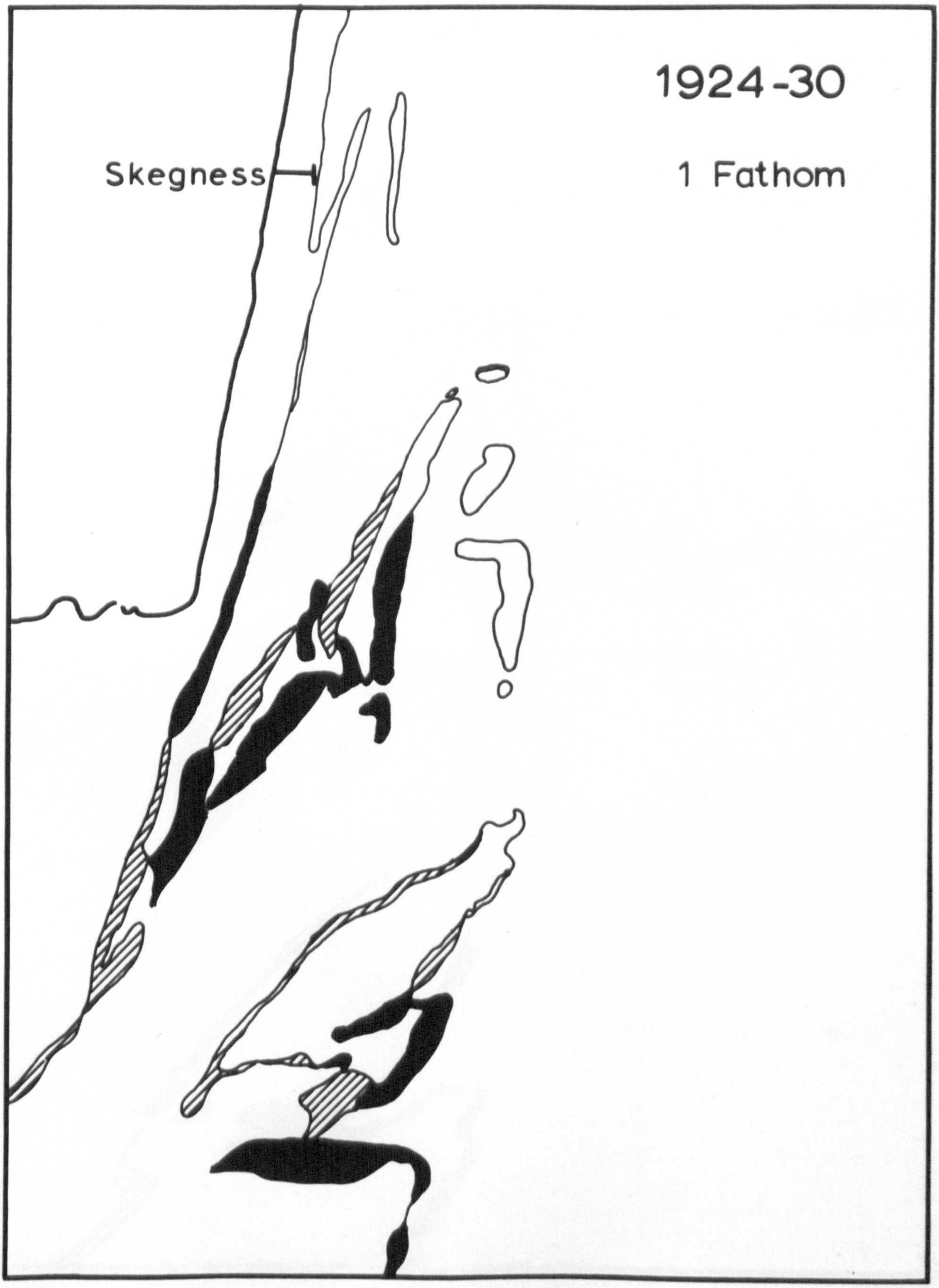


FIGURE 84

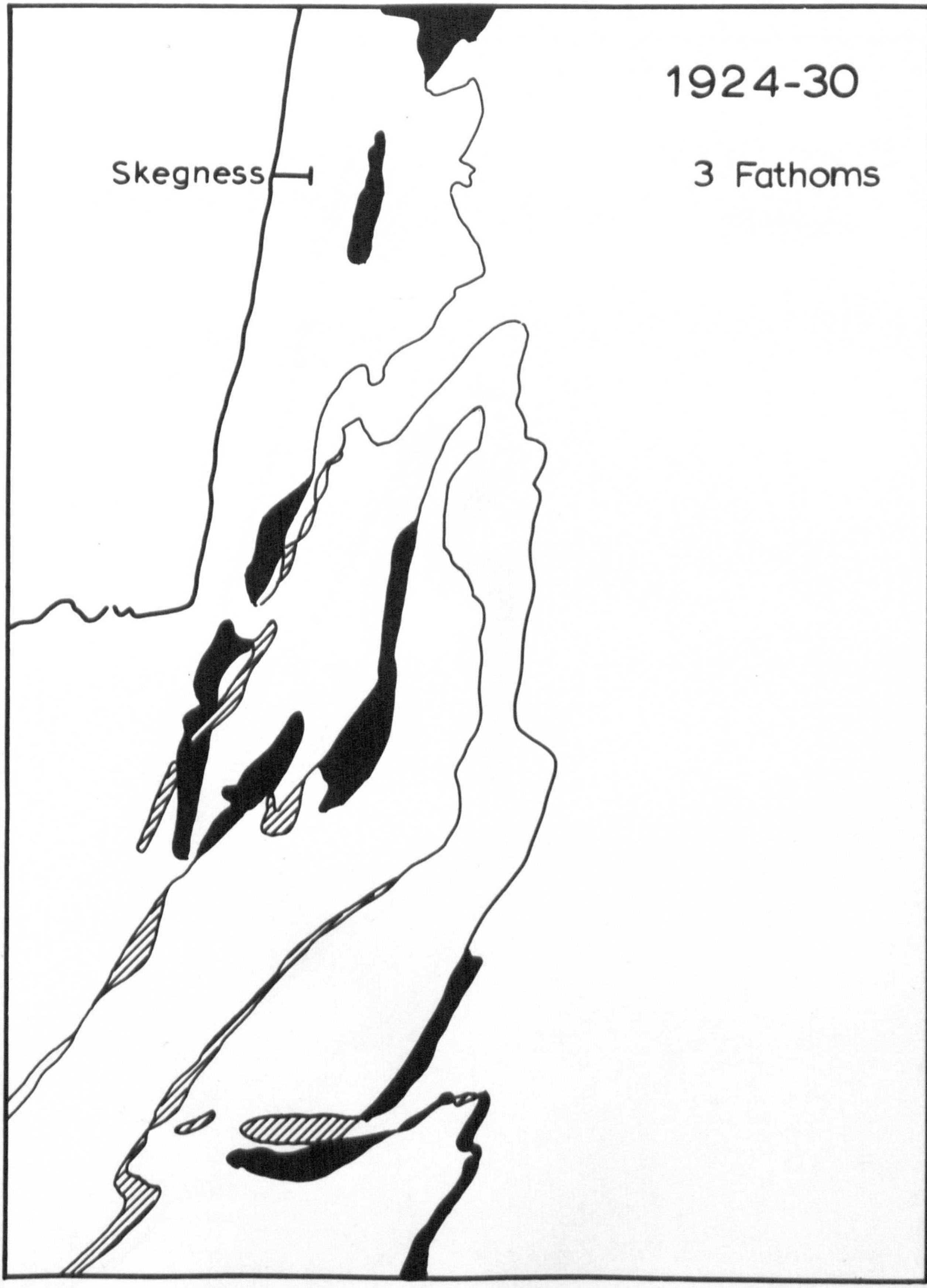


FIGURE 85

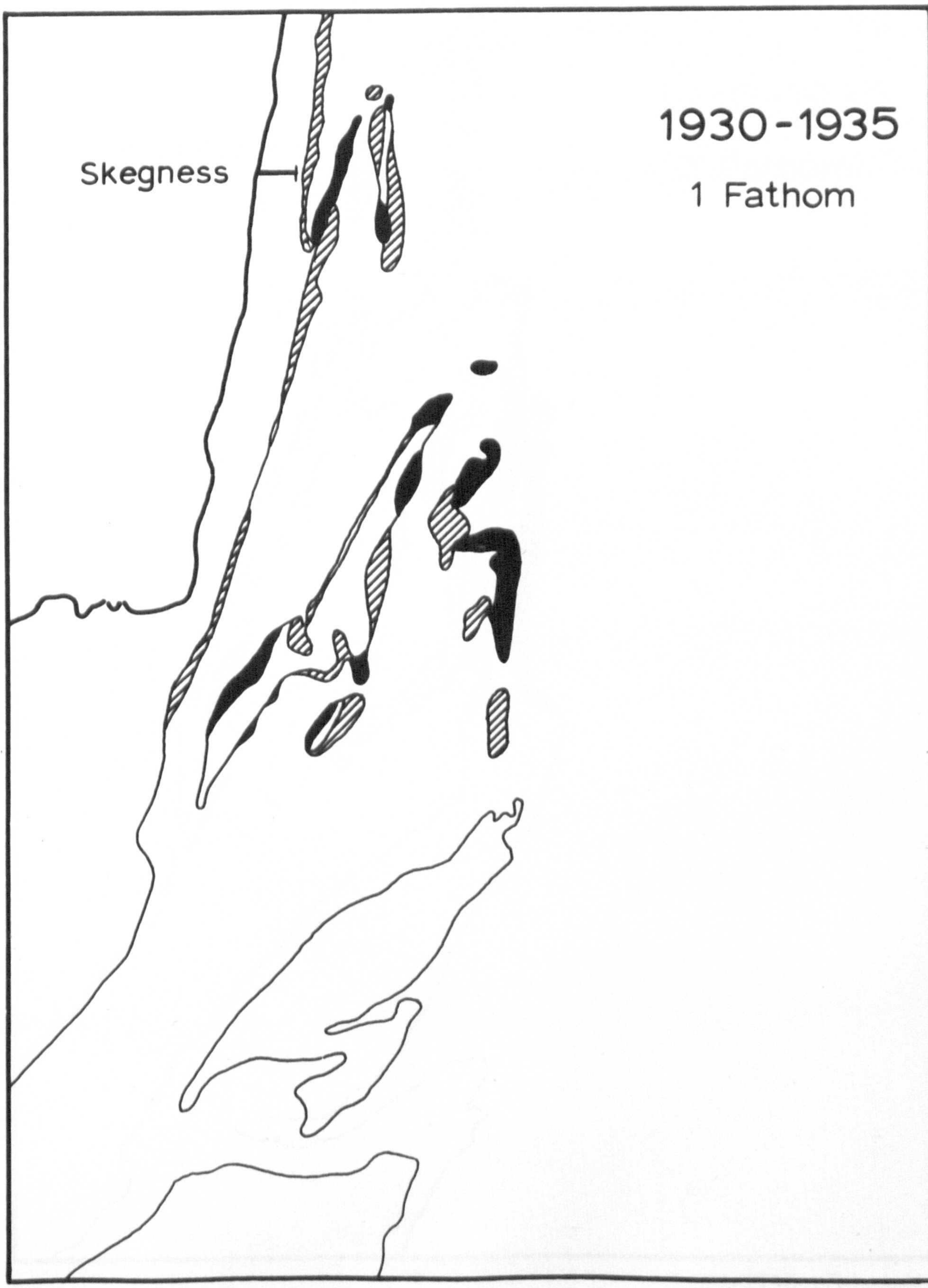


FIGURE 86

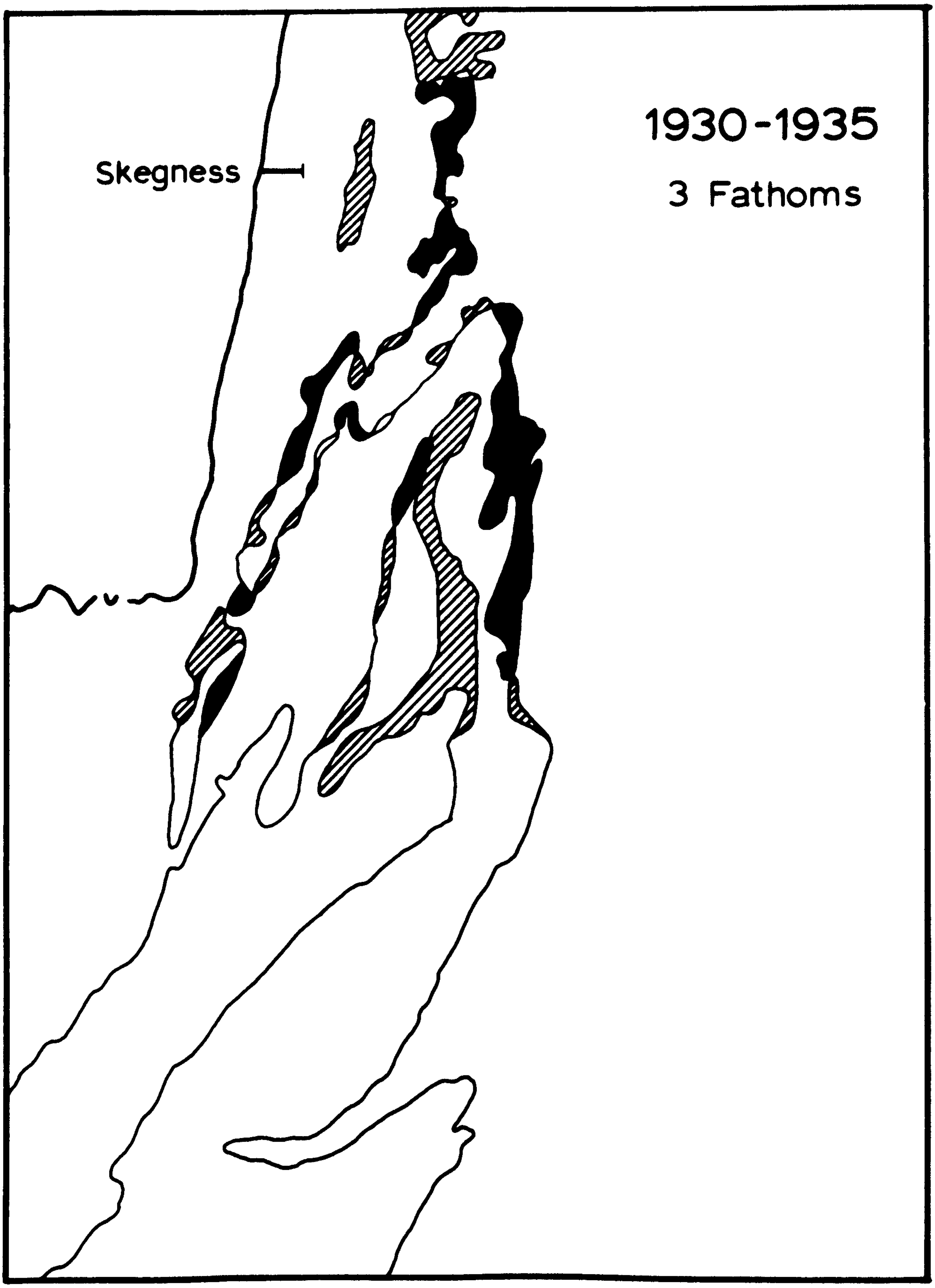


FIGURE 87

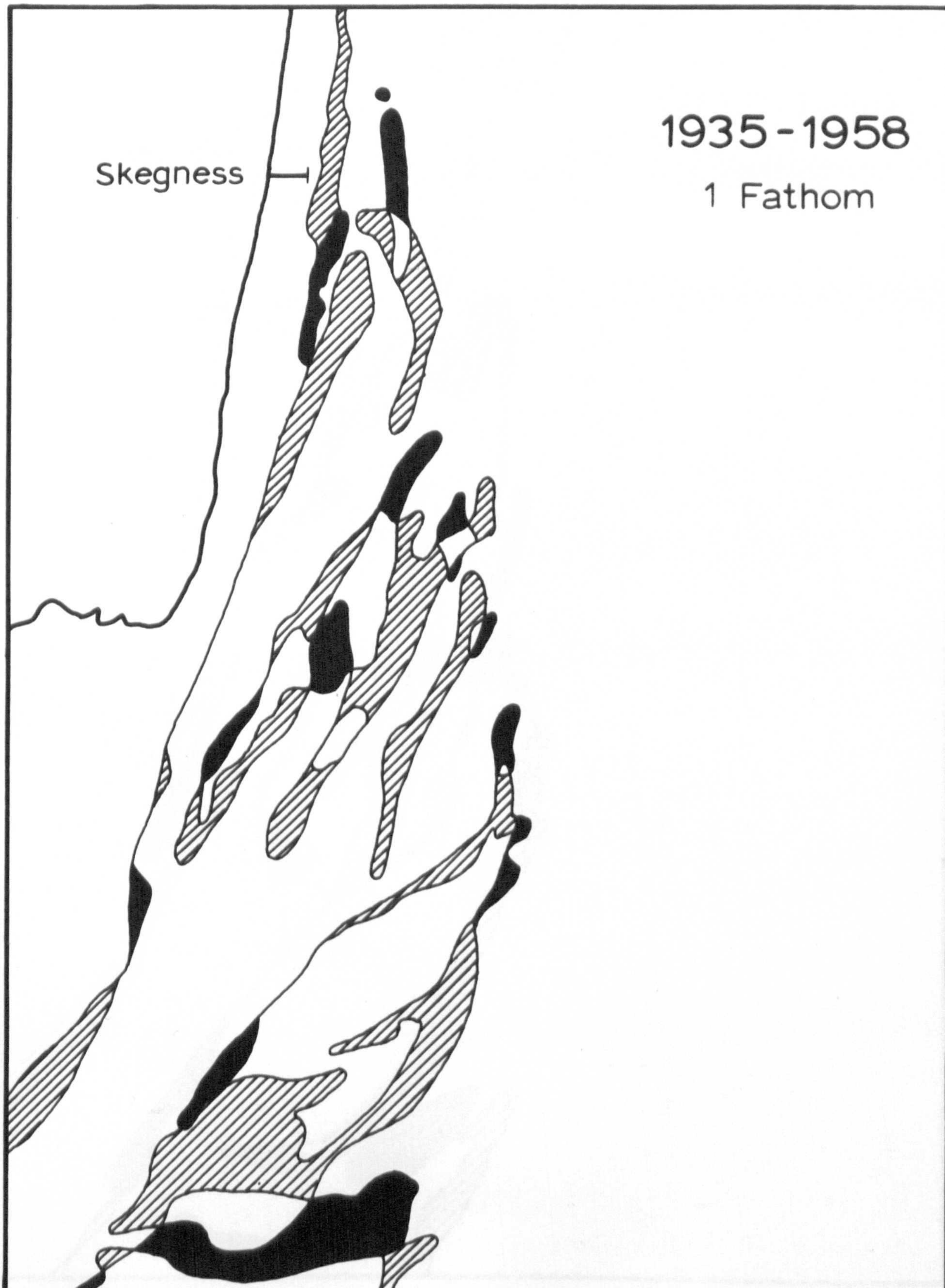
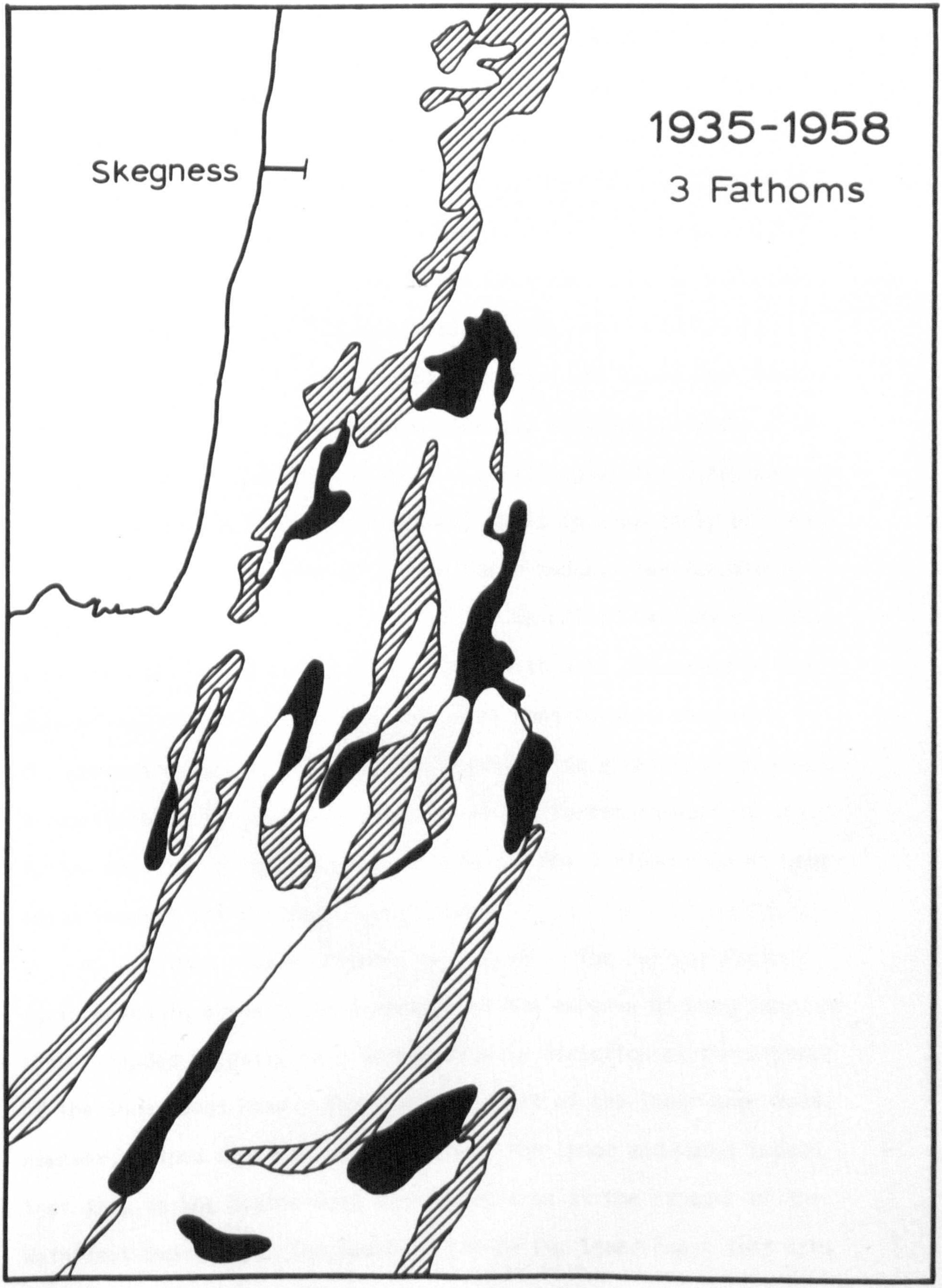


FIGURE 88



Shallowing occurred in the Boston Deep immediately west of the growing Inner Dogs Head. Changes in the remaining parts of the area were confined to the southern portion of the Inner Knock and the infilling of the incipient flood channel separating the Inner and Outer Knocks. The Inner Knock narrowed and extended in a southerly direction at the expense of the Boston Deep. As the Inner Knock moved shoreward a loss occurred on the foreshore area at Gibraltar Point and the Wainfleet Swatchway deepened at this location.

3. 1918 - 1924 (Figures 81 and 82). The Outer Dogs Head generally lost area on the seaward side and extended slightly into the Boston Deep. There was extensive infilling at the north-eastern side of the Boston Deep with a general shift in a westerly direction of the channel at the expense of the Outer Knock. The foreshore extended and a growth in the area of the Wainfleet Swatchway took place at the expense of the Outer Knock with some deepening of the channel near Gibraltar Point. There was considerable deepening in the nearshore zone seaward of the Skegness Middle which moved south. A considerable loss of area occurred on the foreshore west of the former position of the Skegness Middle. A small flood channel developed between the Inner and Outer Knock.

4. 1924 - 1930 (Figures 83 and 84). The Parlour Channel again moved in a southerly direction at the expense of Long Sand and also extended slightly in a north-westerly direction at the expense of the Inner Dogs Head. The remaining part of the Inner Dogs Head, however, gained small amounts of area. The Inner and Outer Knocks lost area to the Boston Deep but gained area at the expense of the Wainfleet Swatchway. The southern tip of the Inner Knock lost area

to a developing southern extension of the Wainfleet Swatchway. A deepening of the Wainfleet Swatchway at Gibraltar Point created a loss of area on the foreshore. The foreshore south of Gibraltar Point, however, gained area. The ebb channel between the limbs of the Skegness Middle deepened.

5. 1930 - 1935 (Figures 85 and 86). The Outer Dogs Head lost area on the seaward side and gained area on the landward side at the expense of the Boston Deep. Losses and gains of area on the Inner Knock, Outer Knock and Wainfleet Swatchway were many but showed no discernable pattern. The western limb of the Skegness Middle decreased in size and the eastern limb increased in area. There was a general gain of area on the foreshore both north and south of the Skegness Middle. The ebb channel between the limbs narrowed.

6. 1935 - 1958 (Figures 87 and 88). There were many changes in sandbank and channel area during this period. The Parlour Channel again moved in a southerly direction at the expense of the northern end of Long Sand. The Inner Dogs Head made large gains of area particularly at the 1 fathom level. The Outer Dogs Head again lost area on the seaward side and gained on the landward side at the expense of the Boston Deep. The Outer Knock split into two distinct sandbanks largely at the expense of the Boston Deep which generally shallowed at the northern end. The Wainfleet Swatchway also showed a general tendancy to shallow although some deepening did occur at the expense of the Inner Knock. The Skegness Middle grew in size and again migrated south. The nearshore area at this location also shallowed.

It should be noted that the bathymetric surveys which form the basis of the above descriptions were not made at equal intervals of time and no information is available regarding the changes of sandbank and channel configuration between the survey periods. Meaningful comment must, therefore, be confined to changes of the configurations of sandbanks and channels which form parts of trends which can be recognised throughout the total period under consideration.

Robinson (1964) conducted a study of changes of sandbank and channel configurations based on Admiralty charts of 1828, 1871, 1918 and 1956. The findings of this study were confirmed by the present analysis and can be summarised as follows. The area of sandbanks which dry at low water has diminished, particularly the Inner Knock, but at the same time the foreshore at Gibraltar Point has widened. The Wainfleet Swatchway has narrowed and deepened and Wainfleet sand has been severed from the foreshore and part has been joined to the southern end of the Inner Knock. The whole sandbank system has moved south a distance of about 1.6 km. since 1828. In recent years a shoal area has developed south from the Outer Knock splitting the northern end of the Boston Deep into two channels. As the inshore channel has developed the Inner Knock has moved nearer to the foreshore and accentuated the tendency of the Wainfleet Swatchway to narrow and deepen.

The following additional trends have been highlighted by the present study. In addition to the Inner Knock the Outer Dogs Head has also shown a consistent tendency to migrate in a shoreward direction. This migration has been achieved by removal of sediment on the seaward side of the sandbank and growth on the landward side at the expense of the Boston Deep. This shoreward migration of the Outer Dogs Head has, therefore, tended to force the Boston Deep in a westerly direction which could, in part, be responsible for the shoreward migration of the Inner Knock which in turn caused the narrowing and deepening of the Wainfleet Swatchway. The apparent southerly movement of the Inner Knock, Outer Knock and Outer Dogs Head recorded by Robinson (1964) has been due to a decrease in the length of the sandbanks rather than an overall trend to migrate in a southerly direction. The southern tips of the Inner Knock and Outer Dogs Head have remained more or less stationary throughout the survey period. A real, as opposed to apparent, southerly movement has occurred in the case of the Skegness Middle sandbank. This sandbank has also shown a consistent tendency to grow in size. Immediately south of the location where the Skegness Middle reaches the shoreline there has always been a small bulge of the foreshore, or ness, which has migrated south with the sandbank. The significance of this feature will be discussed later in this chapter. The Inner Dogs Head has shown a consistent tendency to grow in size. The location of the northern tip of the sandbank has remained stationary and growth has occurred in a southerly direction at the expense of the Parlour Channel which has consistently migrated south at the expense of the northern end of Long Sand.

Actual changes in area of the sandbanks and channels was calculated to determine the presence or absence of sympathetic responses between channel and sandbank systems. For the purpose of this analysis the area was divided into the following zones :-

1. Foreshore and Skegness Middle

2. Wainfleet Swatchway
3. Inner and Outer Knocks
4. Boston Deep
5. Inner and Outer Dogs Head
6. Parlour Channel

Changes in area at the 3 fathom depth level were taken as representative of area changes in the channels, zones 2,4 and 6. Changes in area at the 1 fathom depth level were taken as representative of area changes on the sandbanks and foreshore, zones 1, 3 and 5. For the periods between surveys the following parameters were calculated for the relevant zones :-

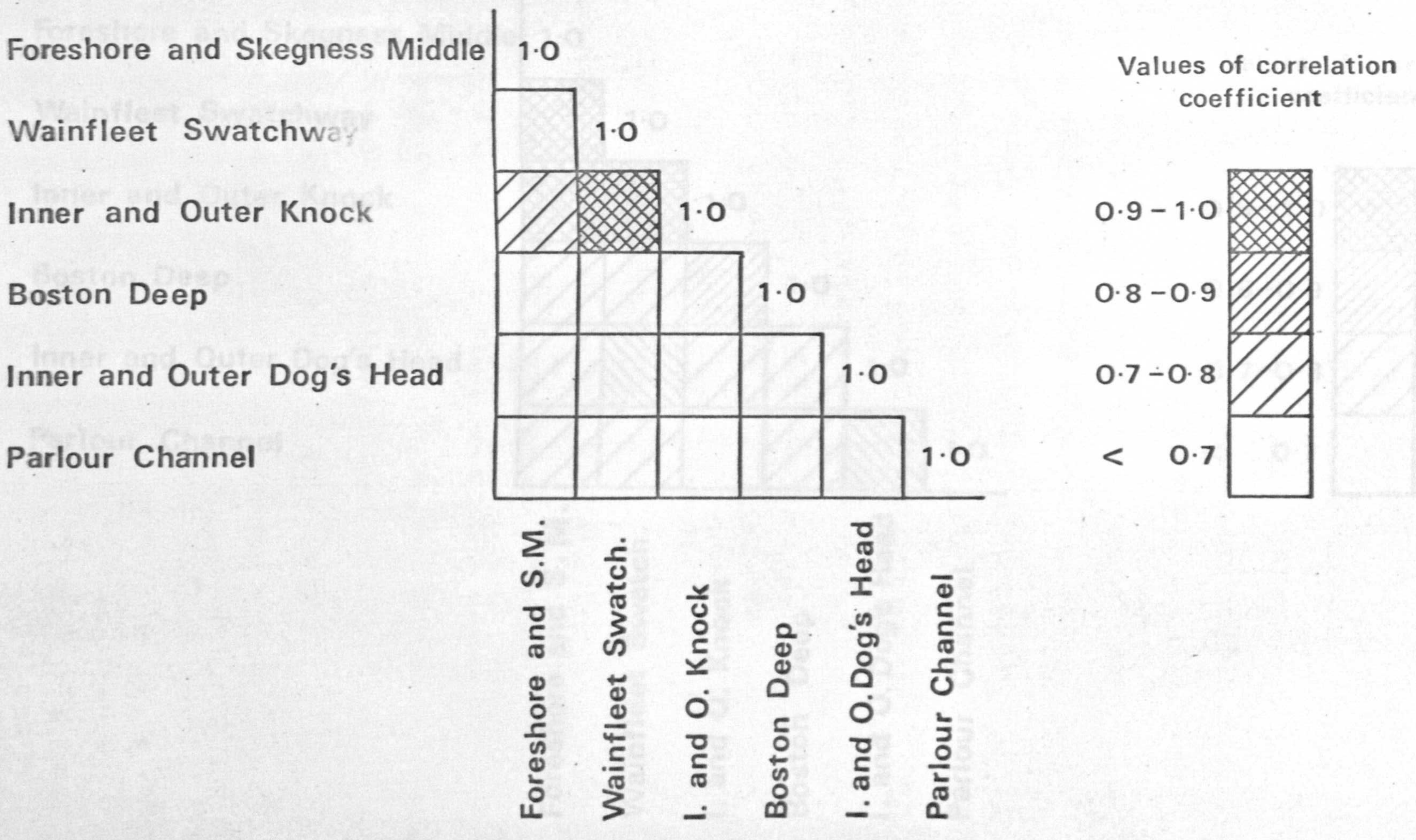
1. Increase in sandbank area
2. Decrease in sandbank area
3. Increase in channel area
4. Decrease in channel area

Correlation matrices were computed for decrease in sandbank area with increase in channel area (Figure 89) and increase in sandbank area with decrease in channel area (Figure 90). No significance levels will be given for the correlation coefficients but the value of the coefficient will be taken as a measure of the linear response, in terms of area change, between one zone and another.

The correlation matrix for the decrease in sandbank area with the increases in channel area (Figure 89) shows the linear relationship between area changes at the 1 fathom and 3 fathom depth levels. The only high correlation coefficient obtained was between the

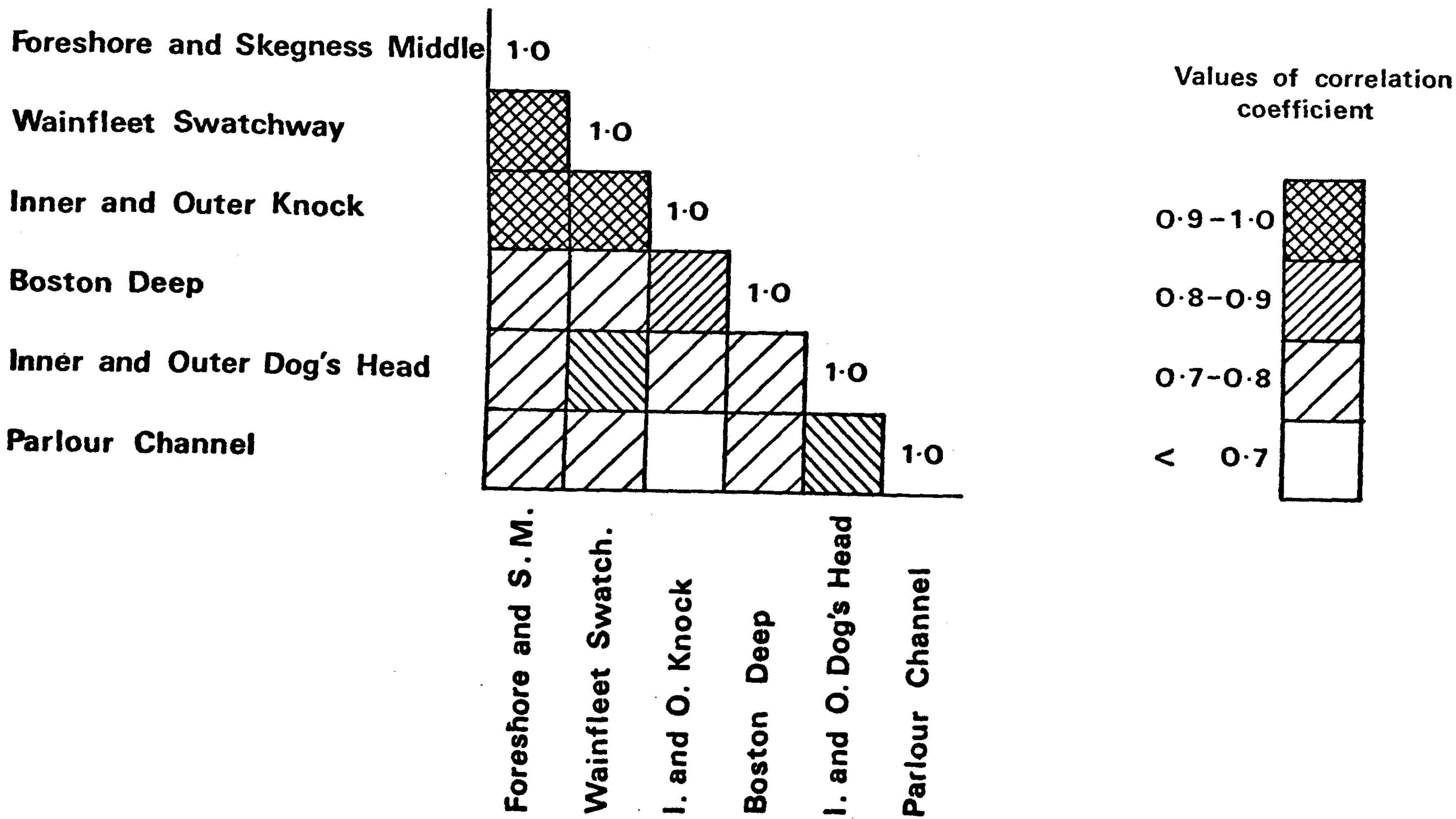
Correlation matrix of decrease in sandbank area with increase in channel area

FIGURE 89



Correlation matrix of increase in sandbank area with decrease in channel area

FIGURE 90



Wainfleet Swatchway and the Inner and Outer Knock sandbank system. In other words during periods when the Wainfleet Swatchway had a tendency to increase in area the Inner and Outer Knock sandbank system had a tendency to decrease in area. In contrast the correlation matrix of increase in sandbank area with decrease in channel area show several high values of correlation coefficients. As the foreshore, Skegness Middle and Inner and Outer Knock sandbank system increased in area the Wainfleet Swatchway decreased in area. Similarly there was a linear, though less strong, response between the growth of the Inner and Outer Knock sandbank system and a decrease in the size of the Boston Deep and the growth of the Inner and Outer Dogs Head sandbank system and a decrease in size of the Parlour Channel.

From the above analysis it would appear to be probable that changes in the size and configuration of the sandbanks and channels is related to the growth of the sandbanks, that is the deposition of sediment, rather than the erosion of sediment comprising the sandbanks by the tidal currents flowing in the channels. Since there appears to be little relationship between an increase in area at the 3 fathom depth level and a decrease in area at the 1 fathom depth level erosion of sediment from the sandbanks must find morphological expression in terms of a steepening of the sides of the sandbanks rather than a removal of sediment from the higher parts of the sandbanks.

DISCUSSION

The major feature in the evolutionary history of the tidal current ridges in the area since 1871 was the growth of the Outer Knock into the northern end of the Boston Deep between the Inner Knock and Outer Dogs Head sandbanks (Figure 76). The Outer Knock at present has the form of a parabolic sandbank with a nose pointing into the ebb tidal currents of the Boston Deep (Chapter 4, this thesis). On the bathymetric charts which were surveyed prior to 1958 the Inner Knock and Outer Knock appear as one linear sandbank, particularly at the 1 fathom depth level, with a small incipient flood channel separating the two sandbanks (Figures 70, 71, 73, 74 and 75). This configuration appears to be similar to stage C in the development cycle for tidal current ridges proposed by Caston (1970) (Figure 69). The Inner Knock and Outer Knock at the present time have reached stages D or E in the development cycle, in plan outline being almost a mirror image of the diagrams presented by Caston (1970). Assuming Castons theory is correct the Inner Knock and Outer Knock should eventually develop into three separate linear sandbanks.

As discussed earlier in this chapter Robinson (1960) suggested changes in size and position of tidal current ridges are probably related to changes in sediment supply or changes in the relative strength of opposing tidal currents. The tidal current ridges in the Skegness area, with the exception of the Skegness Middle, have tended to decrease in areal extent since 1871. The tidal current ridges have also shown a tendency to shorten in linear extent, the decrease in length occurring at the northern ends of the sandbanks. It would be tempting to suggest that this shortening has occurred because of relatively stronger flood tidal currents acting on the northern extremities of the tidal current ridges and removing sediment. However, it has been shown in Chapter 9 that there appears to be a dominant ebb residual of tidal flow as far north as Ingoldmells Point. If this ebb residual does exist north of the tidal current ridges then it would appear that an increase in the relative strength of the flood tidal currents would be unlikely and could not, therefore, be responsible for the shortening of the sandbanks. It would appear that there must have been a decrease in the amount of sediment available for the maintenance of the tidal current ridges and the sandbanks have responded by a shortening of linear extent. Such a conclusion would also help to explain the decrease in areal extent of the tidal current ridges.

The conclusions made earlier in this chapter regarding the mechanisms for changes of configuration of the sandbanks and channels, that is depositional rather than erosional processes, also support the above argument. There is little evidence of decrease in the size of the sandbanks being related to erosion along the flanks of the sandbanks which form the margins of the channels in the area. Also, the depositional processes maintained by a decreased supply of sediment must have responded by creating tidal current ridges of smaller linear and areal extent.

The growth of the Skegness Middle sandbank has largely occurred on the eastern limb which at the present time encloses the ebb dominated northern extremity of the Wainfleet Swatchway (Figure 76). This growth is probably related to the ebb tidal currents in the enclosed channel. The growth of the eastern limb has been associated with a marked shallowing of the entrance to the Wainfleet Swatchway, the Wainfleet Roads, to the south of the Skegness Middle since the 1935 survey (Compare Figures 75 and 76). On all the surveys prior to 1958 the Wainfleet Swatchway and the Wainfleet Roads were part of a continuous flood dominated channel, with depths greater than 3 fathoms, opening in a seaward direction. The shallowing at the mouth of this channel in the Wainfleet Roads suggests that the flood tidal currents are decreasing relative to the ebb tidal currents in the northern parts of the Wainfleet Swatchway and are unable to maintain a continuous channel at depths greater than 3 fathoms. This decrease in the dominance of the flood tidal currents at this location again supports the argument that the shortening of the Inner Knock, Outer Knock and Outer Dogs Head was probably related to a decrease in sediment supply rather than erosion by flood tidal currents of the northern ends of the sandbanks.

It is tempting to suggest that the consistent tendency for the tidal current ridges to decrease in size was in some way related to the consistent tendency for the Inner Dogs Head, an ebb-tidal delta, to increase in size. Such an argument must be highly speculative since, on the basis of information available, no mechanism is known for such a transfer of sediment. A diversion of sediment supply from the tidal current ridges to the Inner Dogs Head would, however, help to explain the decrease in sediment supply associated with the decrease in the linear and areal extent of the tidal current ridges.

The significance of bulges or nesses on the foreshore in close association with tidal current ridges has been discussed by Robinson (1966). In a study on the coast of East Anglia the nesses were found to be attached to submarine sand ridges, tidal current ridges, which extend obliquely from the coast in a seaward direction. The channels shoreward of the ridges were found to be either flood or ebb tide dominated and to be the routes for the migration of sediment from the nearshore zone for subsequent accretion on the foreshore to form the nesses. The Skegness Middle and the flood channel to the west of the sandbank perform an identical role to the features described on the coast of East Anglia. The southerly migration of the ness in sympathy with the Skegness Middle sandbank confirms this relationship. The above argument also confirms the conclusion of the Woodhead seabed drifter experiments, discussed in Chapter 9, that the junction between the Skegness Middle and the foreshore is the major location for movement of sediment from the nearshore to the foreshore in the Skegness area.

The effect of the growth of the ness, as it migrated in a southerly direction, on the cross-sectional profile of the beach has been recorded by King (1973). Survey profiles of the beach taken during the last 25 years at the present location of the ness have shown a greater tendency towards increase in both height and width at this location than at any other location on this part of the Lincolnshire coast. It is perhaps significant that as the Skegness Middle and the associated ness have migrated in a southerly direction since 1871 there has been a tendency for the foreshore to the north to narrow and decrease in height. Despite the building of groynes on this section of the foreshore the removal of the natural protection of a wide and high beach has tended to create problems of coastal erosion in the area around Skegness Pier, particularly during the winters of 1974 and 1975. This tendency may continue and erosion become prevalent if the Skegness Middle continues to migrate in a southerly direction.

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CHAPTER ELEVEN

CONCLUSION

A descriptive sediment movement model has been created for the nearshore zone near Gibraltar Point, Lincolnshire on the basis of evidence from studies of sediments, sandbank and channel morphology, bedforms, measurement of tidal currents and sediment tracer experiments. The model suggested a net northerly movement of sediment in a system composed of tidal current ridges and tidal channels in the area offshore from Gibraltar Point. The largest channel in the area, the Boston Deep, had a large net residual of sediment drift in an ebb or northerly direction which was counteracted by a smaller, flood, or southerly, drift in the contiguous channels, the Wainfleet Swatchway and the Parlour Channel, on either side of the Boston Deep. Movement of sediment across the tidal current ridges separating the channels, the Inner Knock, Outer Knock and Outer Dogs Head, was found to be oblique to the long axes of the sandbanks. A system of tidal current ridges, the Skegness Middle, north of those enclosing the northern end of the Boston Deep, had a net northerly drift of sediment in the channel enclosed between the limbs of the sandbank counteracted by a net southerly drift of sediment in the channels to the west and east of the ebb channel. Movement of sediment along the flood channel to the west of the Skegness Middle was considered to act as a sediment source for accretion on the contiguous foreshore.

The tidal current ridges and tidal channels in the study area were considered to form more or less closed cells of sediment circulation and the tidal current ridges were considered to be sediment traps of a high order of efficiency.

The southern part of the study area contained a large ebb-tidal delta, the Inner Dogs Head, with an associated flood shield and a flood spit. Sediment circulation was considered to be more or less closed around this sandbank.

Woodhead seabed drifter experiments were conducted to assess the validity of the sediment movement model and to determine probable locations on the foreshore for sediment receipt from the nearshore zone. Six releases of seabed drifters were made comprising a total of 300 individual releases. The experiments confirmed the net northerly drift of sediment suggested by the sediment movement model in the nearshore zone south of Skegness. The net northerly drift was found to extend as far north as Ingoldmells Point which was considered to be an area of bedload convergence, the net northerly drift of the Skegness area meeting the net southerly drift along the Lincolnshire coast to the north. A smaller net southerly drift of sediment was considered to be present in the area seaward of the nearshore net northerly drift, associated with the dominant hydrographic feature of the Wash, the Lynn Deep flood channel. Sediments moving south in this zone, seaward of the nearshore zone, were thought to be introduced into the tidal circulation around the tidal current ridges south of Skegness, probably by way of the Parlour Channel, a flood channel opening in a seaward direction.

The locations of strandings of seabed drifters on the foreshore suggested two major zones for sediment movement from the nearshore zone to the foreshore zone. Most strandings occurred on the foreshore between Skegness Pier and the location where the Skegness Middle sandbank meets the foreshore. The preference for drifter strandings in this area confirmed the hypothesis suggested in the sediment movement model that the flood channel between the Skegness Middle and the foreshore is the major route for sediment migration from the nearshore zone to the foreshore zone. A secondary preference for drifter strandings was found at Ingoldmells Point, associated with the bedload convergence in the nearshore zone. Sediment coming ashore at Ingoldmells Point would migrate in a southerly direction along the foreshore under the influence of dominant waves from the north-east. Evidence of such a southerly migration of sediment along the foreshore was noted from the accretion of material on the northern sides of groynes.

Drifter recoveries on the foreshore showed a preference for stranding during periods with offshore winds, periods with wind blowing from the north-east and periods when the tidal currents were increasing in velocity towards spring tide conditions of the spring-neap tidal cycle. On the basis of the evidence available it was not possible to determine the relative importance of these environmental parameters as regards sediment movement from the nearshore to the foreshore zone.

A study of the historical development of the sandbanks in the area based on Admiralty bathymetric charts published since 1871 suggested a general decrease in area of the tidal current ridges and a tencency for a shoreward migration of the sandbanks. A decrease in the amount of sediment available for tidal current ridge maintenance was thought to explain the above trends together with the tendency for the tidal current ridges to decrease in linear extent. However, the general tendency for stability of the tidal current ridges and channels since 1871 was considered to support the conclusions of the sediment movement model that sediment circulation cells are essentially closed.

The southerly movement of a ness, or foreshore bulge, south of the Skegness Middle sandbank was noted to be in sympathy with the migration of the sandbank. The ness was interpreted as being a morphological expression of foreshore adjustment to sediment moving from the nearshore zone to the foreshore zone along the channel between the Skegness Middle and the foreshore.

The study presented in this thesis has contributed to a general understanding of sediment movement in the nearshore zone near Gibraltar Point and has suggested locations on the foreshore that are possible sites for sediment receipt from the nearshore zone. However, there are several aspects of the sediment movement model which are not entirely satisfactory and could provide fruitful avenues for future research. Firstly, the sediment movement model only deals with sand-sized sediments which are usually transported as bedload. A sediment movement model must also account for sediment carried in suspension if the total sediment budget of an area is to be estimated. Secondly, the sediment movement model presented in this thesis cannot be used to predict changes either in sediment transport rate and direction or the morphological response of sandbanks and channels to these changes. The creation of a predictive sediment movement model would require the simultaneous measurement at several locations within the sandbank system of sediment transport rates and energy levels of operative processes over a prolonged period of time and under differing tide and wave conditions. The morphological response of sandbanks and channels to changes in sediment flux would have to be monitored on a very short time scale. Predictive formulae relating sediment transport rates, process energy levels and morphological responses could be created on the basis of the information obtained from the above studies. Such formulae could be used as the basis for a stochastic model for predicting events or changes in the sedimentological and mophological attributes of a nearshore zone dominated by linear tidal currents.